

85

CRANFIELD INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL ENGINEERING

PhD THESIS

Academic Year 1983-1984

P.D. FLEMING

Wind-turbine studies:
the power augmentation of flexible sail systems

Supervisor:

S.D. PROBERT

March 1984

ProQuest Number: 10832170

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10832170

Published by ProQuest LLC (2019). Copyright of the Dissertation is held by Cranfield University.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

SUMMARY

The origin of the wind-turbine is discussed and its subsequent development reviewed.

Various types of sail wind-turbine are described and their advantages and different types detailed. Their appropriateness for driving water pumps in developed, as well as in developing, countries is examined and their benefits for rural communities of less developed countries outlined.

The theoretical analysis of the behaviours of both propeller-type wind-turbines and of two-dimensional yacht sails are reviewed and their possible modifications to describe the performances of flexible-sail wind-turbines discussed.

A novel, variable sail profile, vertical-axis Savonius wind-turbine has been developed and its power characteristics recorded.

Self-regulating peristaltic displacement pumps are proposed to be driven by the horizontal or vertical-axis wind-turbines and their operating characteristics are described. A theoretical analysis relating the torque characteristic of the wind-turbine to that of the pump is outlined.

Data are presented for the power augmentation of a horizontal-axis, flexible-sail type wind-turbine, using a shroud, tip-fins and centre-bodies.

Considerable power enhancements are achievable using the basic, cheap wind-turbine power augmentors tested in this investigation.

SUMMARY OF CONTENTS

1	INTRODUCTION	1
2	THE EVOLUTION OF THE WIND-TURBINE: AN HISTORICAL REVIEW	4
3	SAIL-TYPE WIND-TURBINES	15
4	WIND POWER FOR DEVELOPING COUNTRIES	26
5	HORIZONTAL-AXIS WIND-TURBINE: CURRENT THEORETICAL UNDERSTANDING	36
6	VERTICAL-AXIS WIND-TURBINE: CURRENT THEORETICAL UNDERSTANDING	52
7	SAIL-TYPE WIND-TURBINES: A REVIEW OF PERTINENT THEORETICAL ANALYSES	61
8	HORIZONTAL-AXIS WIND-TURBINE	69
9	VERTICAL-AXIS WIND-TURBINE	81
10	WATER PUMPING	86
11	EXPERIMENTAL TEST FACILITY	95
12	ANALYSIS OF EXPERIMENTAL DATA	113
13	CONCLUSIONS	140

TO MARGARET

ACKNOWLEDGMENTS

I am grateful to Professor S.D Probert for his advice, guidance and constructive criticisms.

Also to the staff of the School of Mechanical Engineering workshops and to the staff of the Cranfield Institute of Technology Library.

Additionally I would like to thank P. Gerish, D. Tanton, S. Arithoppha, Watson-Marlow and Robertson Leaman.

Finally my thanks go to my wife Margaret for her invaluable assistance and support.

CONTENTS

SUMMARY	(i)
SUMMARY OF CONTENTS	(ii)
ACKNOWLEDGEMENTS	(iv)
LIST OF CONTENTS	(v)
LIST OF FIGURES	(x)
LIST OF TABLES	(xv)
LIST OF PLATES	(xv)
NOTATION	(xvi)

CHAPTER ONE

INTRODUCTION

1.1	AIMS OF THE RESEARCH	1
1.2	LITERATURE REVIEW	2
1.2.1	Horizontal-axis	2
1.2.2	Vertical-axis	2
1.2.3	Theoretical analysis of wind-turbine flexible sails	2
1.2.4	Positive-displacement pump	3
1.3	PRESENT RESEARCH	3

CHAPTER TWO

THE EVOLUTION OF WIND-TURBINES: AN HISTORICAL REVIEW

2.1	EARLY DEVELOPMENTS	4
2.2	TWENTIETH CENTURY WIND POWER UTILISATION	7
2.2.1	Horizontal-axis wind-turbines	7
2.2.2	Vertical-axis wind-turbines	10
2.3	POST-1973 AND FUTURE DEVELOPMENTS	12

CHAPTER THREE

SAIL-TYPE WIND-TURBINES

3.1	FLEXIBLE SAILS	15
3.2	HORIZONTAL-AXIS WIND-TURBINES	16
3.2.1	Cretan	16
3.2.2	Thai	17
3.2.3	Madurai	17
3.2.4	Omo	17
3.2.5	N.A.L.	18

3.3	VERTICAL-AXIS WIND-TURBINES	18
3.3.1	Chinese	18
3.3.2	Campbell Chinese-type wind-turbine	19
3.3.3	I.A.S.	19
3.3.4	S.W.D.	19
3.3.5	Low energy systems	19
3.3.6	"Starter bucket" for Darrieus rotors	20
3.3.7	Sail-wing Darrieus	20
3.4	WIND-DRIVEN WATER PUMP	21
3.5	WIND-DRIVEN WATER PUMP APPLICATIONS	22
3.5.1	Water raising in less-developed countries	22
3.5.1.1	Crop irrigation	22
3.5.1.2	Water for domestic use	23
3.5.2	UNITED KINGDOM APPLICATIONS	23
3.5.2.1	Irrigation	23
3.5.2.2	Boosted thermo-syphon system	24

CHAPTER FOUR

WIND POWER FOR DEVELOPING COUNTRIES

4.1	INTERNATIONAL PERSPECTIVE	26
4.2	AID PROGRAMMES TO LESS-DEVELOPED COUNTRIES	27
4.3	IRRIGATION	30
4.4	HEATING AND LIGHTING	30
4.5	RURAL ELECTRIFICATION	31
4.6	SAIL TYPE WIND-TURBINES AS A POWER SOURCE	32
4.7	POTENTIAL EXPLOITATION	34

CHAPTER FIVE

HORIZONTAL-AXIS WIND-TURBINES: CURRENT THEORETICAL UNDERSTANDING

5.1	THE ENERGY IN THE WIND	36
5.2	WIND-TURBINE DIMENSIONLESS COEFFICIENTS	37
5.2.1	Lift and drag coefficients	37
5.2.2	Power coefficient	39
5.2.3	Tip-to-wind speed ratio	40
5.2.4	Torque coefficient	40
5.2.5	Solidity ratio	41
5.3	ANALYSIS OF WIND-TURBINE POWER CHARACTERISTICS	41
5.3.1	Maximum power available in the wind	41
5.4	REDUCTIONS IN THE THEORETICAL MAXIMUM POWER OUTPUT	44
5.4.1	Wake rotation	44
5.4.1.1	Derivation of an expression for the maximum power output of a wind-turbine	45
5.4.2	The effect of lift and drag	48
5.4.3	Tip losses	50
5.5	CASCADE THEORY	50
5.6	CURRENT UNDERSTANDING	51

CHAPTER SIX

VERTICAL-AXIS WIND-TURBINES: CURRENT THEORETICAL UNDERSTANDING

6.1	THE ENERGY IN THE WIND	52
6.2	GENERAL THEORETICAL ANALYSIS	53
6.3	DIMENSIONAL ANALYSIS OF THE SAVONIUS PANEMONE	53
6.4	POWER COEFFICIENT	55
6.4.1	Reductions in theoretical maximum power outputs	56
6.4.1.1	End losses	56
6.4.1.2	Side losses	57
6.5	DIRECTION OF THE MAGNUS FORCE	58
6.6	CURRENT UNDERSTANDING	60

CHAPTER SEVEN

SAIL-TYPE WIND-TURBINES: A REVIEW OF PERTINENT THEORETICAL ANALYSES

7.1	INTRODUCTION	61
7.2	AERODYNAMICS OF YACHT SAILS	61
7.2.1	The sail	62
7.2.2	Previous research on two-dimensional flexible yacht sails	63
7.3	AERODYNAMICS OF WIND-TURBINE FLEXIBLE SAILS	64
7.3.1	Previous investigations into the theoretical analyses of wind-turbine flexible sails	65
7.4	TWO-DIMENSIONAL SAIL EQUATION	66
7.5	PROPOSED FUTURE RESEARCH	68

CHAPTER EIGHT

HORIZONTAL-AXIS WIND-TURBINE

8.1	THE ROTOR	69
8.1.1	The sails	69
8.1.1.1	The sail angle	69
8.1.1.2	The spoke angle	70
8.1.1.3	The solidity ratio	70
8.2	POWER AUGMENTORS	70
8.2.1	The shroud	70
8.2.2	Tip-fins	72
8.2.3	Centre-bodies	74
8.2.4	Tip-fin and centre-body combined	78
8.3	THE ECONOMIC VIABILITY OF POWER AUGMENTORS	80

CHAPTER NINE

VERTICAL-AXIS WIND-TURBINE

9.1	ADVANTAGES OF VERTICAL-AXIS WIND-TURBINES	81
9.2	THE SAVONIUS WIND-TURBINE	81
9.3	PROPOSED SAIL VERSION OF THE SAVONIUS-TYPE WIND-TURBINE	83
9.3.1	Power augmentation devices	84
9.4	FINALLY CHOSEN DESIGN	85

CHAPTER TEN

WATER PUMPING

10.1	WIND-TURBINE AND PUMP MATCHING	86
10.2	PERISTALTIC PUMP — COMMERCIALY-AVAILABLE DESIGN	89
10.2.1	Pump operation	90
10.2.1.1	Horizontal-axis wind pump	91
10.2.1.2	Vertical-axis wind pump	92
10.2.1.3	Regulating spring	92
10.2.2	Maintenance	92
10.3	LOW TECHNOLOGY PERISTALTIC PUMP	93
10.3.1	Pump operation	93
10.3.2	Pump construction	94

CHAPTER ELEVEN

EXPERIMENTAL TEST FACILITY

11.1	THE WIND TUNNEL	95
11.1.1	Blockage effects	98
11.1.1.1	Horizontal-axis wind-turbine	98
11.1.1.2	Vertical-axis wind-turbine	98
11.1.2	The fan	99
11.1.3	The afterbody	99
11.2	WIND-TURBINE SUPPORT STRUCTURES	99
11.2.1	Horizontal-axis	99
11.2.1.1	Shrouded test sequence	99
11.2.1.2	Unshrouded test sequence	100
11.2.2	Vertical-axis	103
11.3	TORQUE MEASUREMENT	106
11.3.1	Horizontal-axis	107
11.3.2	Vertical-axis	110
11.4	ROTOR SPEED MEASUREMENT	110
11.5	WIND SPEED MEASUREMENT	111
11.6	WIND-TURBINE POWER OUTPUTS	111
11.6.1	The product of torque and rotor speed	111
11.6.2	Hydraulic power	111
11.7	EXPERIMENTAL PROCEDURE	112

CHAPTER TWELVE

ANALYSIS OF EXPERIMENTAL DATA

12.1	INTRODUCTION	113
12.2	WIND SPEED	113
12.3	HORIZONTAL-AXIS WIND-TURBINE	114
12.3.1	Shrouded wind-turbine measurements	114
12.3.2	Tip-fins augmented wind-turbine measurements	120
12.3.3	Centre-body augmented wind-turbine measurements	125
12.3.4	Tip-fin and centre-body augmented wind-turbine measurements	128
12.4	VERTICAL-AXIS WIND-TURBINE	133
12.4.1	Taut sail profile vertical-axis wind-turbine measurements	135
12.4.2	Variable sail profile vertical-axis wind-turbine measurements	138

CHAPTER THIRTEEN

CONCLUSIONS

13.1	CONCLUSIONS	140
13.2	RECOMMENDATIONS FOR FUTURE RESEARCH	142

REFERENCES	143
------------	-----

APPENDICES	152
------------	-----

A	SAIL-TYPE WIND-TURBINES: A REVIEW AND ANNOTATED BIBLIOGRAPHY	152
B	SAIL-TYPE WIND-PUMP DATA	166
C	DESIGN OF A 1.25 m DIAMETER WIND TUNNEL	168
D	DEMONSTRATION PROJECT	172
E	EQUIPMENT USED	176
F	EXPERIMENTAL ERRORS	177

FIGURES

	PAGE
1. Basic features of the traditional "Cretan" type wind-turbine.	16
2. Traditional Chinese-type wind-turbine.	18
3. Sail-type wind-turbine developed by Low Energy Systems.	20
4. Schematic representation of the boosted thermo-syphon closed circuit. (Except for the "radiators" all the circuitry is extremely well insulated thermally).	24
5. Air of volume flow rate $\dot{V}$ flowing through a disc of area A.	37
6. Diagram showing angle of attack, chord line and forces acting on an aerofoil.	38
7. Schematic representation of the flow through the wind-turbine.	42
8. Wind-turbine blade annulus at radius r.	44
9. Schematic representation of the flow through the wind-turbine with wake rotation.	45
10. Power coefficient as a function of tip-to-wind speed ratio of an ideal wind-turbine.	47
11. The influence of the ratio of lift to drag coefficients on wind-turbine performance for an ideal wind-turbine.	48
12. Velocities and forces on a blade element at radius r.	48
13. Nomenclature of the Savonius wind-turbine.	53
14. Schematic representaion of the flow through a two-vaned Savonius wind-turbine.	57
15. Wind deflectors for a sail-type Savonius wind-turbine. The deflectors are rigidly connected and rotate about the common axis. By means of a tail-vane they would always be aligned with the wind.	57
16. Velocity nomenclature in the x-y plane.	58
17. Pressure P_s at a point on the boundary of a cylinder.	59

18.	Direction of the Magnus force on a rotating cylinder in a uniform air stream.	60
19.	Nomenclature for a two-dimensional sail at an angle of incidence α to the wind.	62
20.	Sail co-ordinate system and notation.	66
21.	The tension distribution experienced by a sail element.	67
22.	(a) Elastic sail attachment; and (b) shock cord.	70
23.	Schematic representation of the location of the tested wind turbine (of 0.64 m diameter) within the wind tunnel (of 0.84 m diameter).	70
24.	Stream tube for air flowing through a wind-turbine in free-air conditions.	71
25.	(a) Stream tube for air flowing through a conventional horizontal-axis wind-turbine; (b) Stream tube for air flowing through a wind-turbine of Fig. 25 (a), which is now enclosed within a shroud.	73
26.	Stream-tube for air flowing through a tip-fin augmented version of Fig. 25 (a).	73
27.	Tip-fin (tipvane) on a rigid propeller, as conceived by van Holten (Ref. 129).	74
28.	Centre-body augmented wind-turbine.	75
29.	Centre-body and tip-fin augmented wind-turbine.	79
30.	The conventional Savonius wind-turbine.	82
31.	The three flexible sail Savonius-type vertical-axis wind-turbine: schematic representation of the flows and of the sail profiles.	84
32.	(a) Power coefficient; and (b) torque coefficient; of a sail-type wind-turbine, versus its tip-to-wind speed ratio.	86
33.	The pumping power of a wind-turbine and pump combination, as a function of wind velocity. Pumping power and wind velocity are expressed dimensionlessly in terms of the design parameters, P_0 and u_0 , respectively.	88
34.	The power coefficient of a wind-turbine and pump combination against the non-dimensional wind speed parameter $\frac{u}{u_0}$.	89
35.	Schematic representation of the commercially-available peristaltic pump: its components and operation, (a) Typical drive unit position, one roller is shown	90

completely compressing the tube; (b) Unique situation with both tapered rollers compressing the tube.	
36. Self-regulating peristaltic pump for the horizontal-axis wind-turbine; (a) Starting mode; (b) normal operation and (c) over-speed mode. For clarity, only the two rollers actually compressing the tube (in position AA of Fig. 35 (b)) are shown in the drawing.	91
37. Self-regulating peristaltic pump for the vertical-axis wind-turbine; again with both tapered rollers squashing the tube. (For part of the time, only one roller is in contact with the flexible tube).	92
38. Low technology peristaltic pump.	93
39. Wind tunnel velocity profiles.	98
40. Wind tunnel, fan and fan after-body.	99
41. Shrouded wind-turbine support structure.	99
42. Shrouded wind-turbine bearing housing and speed measuring equipment.	100
43. Unshrouded wind-turbine bearing housing and speed measurement.	100
44. Vertical-axis wind-turbine constructional details.	103
45. Vertical-axis wind-turbine upper support-shaft assembly.	106
46. Horizontal-axis wind-turbine torque measurement arrangement.	107
47. Vertical-axis wind-turbine torque measurement arrangement.	110
48. Schematic representation of hydraulic power measurement equipment.	112
49. Comparison of the wind-turbine performance using either rim-attached sails or sail-with-pole configuration: sail area against maximum rotational speed.	115
50. Comparison of the wind-turbine performance using either rim-attached sails or sail-with-pole configuration: sail angle against maximum rotational speed.	115
51. The effect of sail angle on the power output characteristics of the wind-turbine with test system A6.	116
52. The effect of sail angle on the torque characteristics of the wind-turbine with test system A6.	116

FIGURES

PAGE

53.	The effect of sail angle on the power output characteristics of the wind-turbine with test system A7.	117
54.	The effect of sail angle on the torque characteristics of the wind-turbine with test system A7.	117
55.	The effect of sail angle on the power output characteristics of the wind-turbine with test system A8.	117
56.	The effect of sail angle on the torque characteristics of the wind-turbine with test system A8.	118
57.	The effect of sail angle on the power output characteristics of the wind-turbine with test system A9.	118
58.	The effect of sail angle on the torque characteristics of the wind-turbine with test system A9.	118
59.	The effect of sail angle on the maximum power harnessed by the wind-turbine with test systems A6, A7, A8, and A9.	119
60.	(a) Rotor segment showing tip-fin position. (b) Tip-fin position tested and sail profile. (The four dots on the rim represent anchorage points for the wheel spokes).	120
61.	Tip-fin augmented wind-turbine — tested tip-fins (see also Table 4).	121
62.	The influence of tip-fin position on wind-turbine power characteristics; nine tip-fins, type A, were used throughout.	122
63.	The dependence of the wind-turbine power characteristics upon the number of tip-fins, each of type A.	122
64.	The effects of tip-fin inclination (to the undisturbed wind direction) upon the wind-turbine power output: nine tip-fins, each in position I were used for this sequence of tests.	123
65.	Wind-turbine power output as a function of tip-fin length: nine fins, each in position I, were used.	123
66.	How wide tip-fins and tip-fins projecting both up-wind and down-wind affect the wind-turbine power characteristics: Nine tip-fins, each in position I were adopted.	124
67.	Dimensions of the hub-fairings and after-bodies tested.	126
68.	Power characteristics of the wind-turbine augmented by rotating or stationary hub-fairings, with no after-body present.	126

69.	Power characteristics of the wind-turbine augmented by rotating or stationary hub-fairings with after-body A1 (as shown in Fig. 67).	127
70.	Power characteristics of the wind-turbine augmented by rotating or stationary hub-fairings with after-body A2 (as shown in Fig. 67).	127
71.	Tip-fin and centre-body augmented wind turbine — schematic representation of the tip-fins tested.	129
72.	The effects of centre-bodies and tip-fins on the wind-turbine power output (Hub-fairing S2 and flat tip-fins, 52 mm wide, projecting down-wind, by 76 mm, were employed for this series of tests.	129
73.	The effects of tip-fin width on the wind-turbine's maximum power output. The tip-fin length down-wind remained invariant at 76 mm for this sequence of tests.	130
74.	The influence of tip-fin length up-wind on the wind-turbine's maximum power output. Tip-fins 25 mm wide, projecting 76 mm down-wind were employed for this sequence of tests.	130
75.	The effects of tip-fin inclination (relative to the undisturbed wind direction) up-wind on the wind-turbine's maximum power output. Fins 25 mm wide, projecting 76 mm down-wind and 10 mm up-wind were employed in this series of tests.	131
76.	The influence of tip-fin inclination (relative to the undisturbed wind direction) down-wind on the wind-turbine's maximum power output. Fins 25 mm wide, projecting up-wind by 10 mm at angle of 5 degrees and projecting down-wind by 76 mm were used.	131
77.	The influence of tip-fin tilt angle (relative to the rotor rim) on the maximum power output of the wind-turbine. Flat tip-fins, 25 mm wide, projecting up-wind by 10 mm and down-wind by 76 mm were employed.	132
78.	Outline of the Savonius sails tested — the sail material is rip-stop nylon.	133
79.	Savonius wind-turbine — sail types A and B with elastic sail attachments.	134
80.	Savonius deflector for "short" sails.	135
81.	The effect of sail profile on the Savonius wind-turbine's power output: sail area A, see Fig. 79.	135

FIGURES

PAGE

82.	The effect of sail profile on the Savonius wind-turbine's power output: sail area B, see Fig. 79.	136
83.	The effect of solidity on the Savonius wind-turbine's power output: sail profile 3, see Fig.78.	137
84.	Comparison of the power outputs for the two- and three-sail Savonius wind-turbines.	137
85.	Power characteristics for the Savonius wind-turbine with a taut sail profile and with a variable sail profile.	139
86.	Proposed wind tunnel.	171
87.	Horizontal-axis demonstration wind-turbine .	173
88.	Vertical-axis demonstration wind-turbine.	174

TABLES

1.	Aid given to Developing countries during 1980. (Based upon DAC Chairman's report, 1981).	27
2.	Typical present order of priority for energy use in less developed countries.	30
3.	Shrouded wind-turbine test systems — nine individual sails on the 0.64 m diameter rotor. The sail were made of Melinex, 0.125 mm thick.	114
4.	Tip-fin augmented wind-turbine, tested plane, or angled tip-fins. (All were made from 1.5 mm thick dural sheet).	121

PLATES

1.	Tip-fin and centre-body augmented horizontal-axis wind-turbine.	76
2.	Wind tunnel and ancillary measuring equipment with the horizontal-axis test wind-turbine in situ.	96
3.	Horizontal-axis wind-turbine support structure.	101
4.	Vertical-axis wind-turbine support structure.	104
5.	Vertical-axis wind-turbine — central shaft, lower support plate and bearing assembly.	108
6.	Square-section wind tunnel.	169

NOTATION ACCORDING TO LOCAL CONTEXT

a	speed of sound	(ms ⁻¹)
a	axial interference factor	(-)
a'	tangential interference factor	(-)
A	stream-tube or wind-turbine, cross-sectional area	(m ²)
A	area swept by the Savonius wind-turbine	(m ²)
B	the number of wind-turbine sails or blades	(-)
B	fluid compressibility	(Nm ⁻²)
c	chord of blade or sail	(m)
C _D	drag coefficient	(-)
C _L	lift coefficient	(-)
C _P	power coefficient	(-)
C _Q	torque coefficient	(-)
C _x	sectional force coefficient in the x direction	(-)
C _y	sectional force coefficient in the y direction	(-)
C _f	pressure coefficient on a Savonius wind-turbine	(-)
D	drag force	(N)
d	diameter of the Savonius rotor	(m)
f()	function of ()	(-)
F _m	Magnus force	(N)
F _t	tangential force on the rotor	(N)
F _x	force in the x direction	(N)
F _y	force in the y direction	(N)
l	length of sail	(m)
L	lift force	(N)
$\dot{M}$	rate of change of momentum	(kgms ⁻²)
$\dot{m}$	mass flow rate of air	(kgs ⁻²)
p	static pressure	(Nm ⁻²)
P	mechanical power output of the wind-turbine	(W)
P _{air}	power available in the wind	(W)
P _{max}	maximum theoretical power output of the wind-turbine	(W)
p _b	static pressure at the cylinder boundary	(Nm ⁻²)
p _o	static pressure at a point remote from the cylinder	(Nm ⁻²)
Q	torque generated by the wind-turbine	(Nm)
r	rotor radius	(m)
R	radius of the wind-turbine	(m)
T	thrust on an element of the rotor blade (or propeller)	(N)
T	tension in the sail	(Nm ⁻¹)
U	wind velocity	(ms ⁻¹)
u	wind-velocity through the rotor	(ms ⁻¹)
v	component of velocity	(ms ⁻¹)
V	forward speed in the direction of the axis of rotation	(ms ⁻¹)
$\dot{V}$	volumetric flow rate	(m ³ s ⁻¹)
W	relative velocity through the rotor	(ms ⁻¹)
z	distance apart of the Savonius rotor end plates	(m)

NOTATION

α	aerofoil angle of attack	(-)
β	sail angle	(-)
γ	slope of the sail	(-)
δ	Savonius wind-turbine speed ratio	(-)
Δ	small increment of	(-)
η	efficiency	(-)
θ	angle between the radial velocity component and the x-axis	(-)
λ	tip-to-wind speed ratio	(-)
μ	fluid dynamic viscosity	(Nsm ⁻²)
x	x-variable of integration	(-)
ρ	density of the fluid	(kgm ⁻³)
σ	wind-turbine solidity ratio	(-)
σ	coefficient of porosity	(-)
Γ	circulation	(m ² s ⁻¹)
ϕ	angle between the plane of rotation and the relative flow velocity in the plane of rotation	(-)
$\phi()$	Function of ()	(-)
ψ	vortex strength	(m ² s ⁻¹)
ω	rotational speed of the rotor	(s ⁻¹)
ω	angular velocity of the wake	(s ⁻¹)

SUBSCRIPTS

o	when the wind-turbine power coefficient is at its maximum
1	far up-stream of the wind-turbine
2	far downstream of the wind-turbine
r	at the rotor
r	radial component of velocity
t	tangential component of velocity

CHAPTER 1

INTRODUCTION

1.1 AIMS OF THE RESEARCH

Considerable development effort is said to be required to optimise the designs of flexible sail wind-turbines (Ref. 1). This thesis aimed at undertaking such an optimisation by employing shrouds, tip-fins and centre-bodies to augment the power outputs of a horizontal-axis wind-turbine. It also aimed at developing a vertical-axis, variable sail profile Savonius-type wind-turbine and assessing the appropriateness of flexible-sail wind-turbines for driving water pumps in rural communities of the Third World.

Relatively expensive and complex augmentation devices are currently being investigated for use with propeller-type wind-turbines (Ref. 2). This research investigation endeavoured to simplify the proposed devices and reduce their costs. These power augmentation techniques could then be applied to vertical as well as horizontal-axis sail-type wind-turbines and design optimisation undertaken.

No theoretical analysis of the behaviours of wind-turbine flexible sails exists and the objective of the following research was to provide a first step towards this goal. It also aimed at increasing our knowledge of the behaviour of wind-turbine augmentation devices and of the matching of the turbines to peristaltic pumps.

Thus the overall objective was to develop cheap power augmented sail type wind-turbines capable of driving self-regulating peristaltic pumps for irrigation. These "wind-pumps" would be capable of operating in relatively low speed winds ($\sim 5 \text{ ms}^{-1}$) with minimal maintenance. They would be suitable for use in both developed and less-developed countries; i.e. raising water for crop irrigation, stock watering and for domestic use.

INTRODUCTION LITERATURE REVIEW

1.2 LITERATURE REVIEW

1.2.1 Horizontal-axis

There has been substantial research effort directed at horizontal-axis sail-type wind-turbines, (Refs. 3 to 6) but there are few investigations concerning their testing under "laboratory conditions". Dekker (Ref. 7) and Calvert (Ref. 8) present experimental data for "Cretan-type" sail wind-turbines, but the majority of the other papers concern the "field testing" of water pumping sail-type wind-turbines. Despite a comprehensive literature search (see Appendix A), no information was forthcoming concerning the power augmentation of flexible-sail wind-turbines. Although propeller-type wind-turbines have been used with shrouds (Refs. 9 and 10), tip-fins (Ref. 2), and centre-bodies (Refs. 11 and 12), these devices have been relatively complex and expensive additions — the augmentors that have been employed with the wind-turbines reported here are basic, cheap and simple devices.

1.2.2 Vertical-axis

There is considerable literature refering to metal-vaned Savonius (Refs. 13 to 15) and Darrieus-type (Ref. 16) wind-turbines and to the augmentation of rigid profile Savonius rotors, using a variety of concentrators and deflectors (Refs. 17 to 19), but references to sail-type Savonius wind-turbines are more obscure. Campbell (Ref. 20), proposed a modified version of traditional Chinese-type rotor, Hurley (Ref. 21), described a variable sail profile Darrieus-type wind-turbine and Newman and Ngabo (Ref. 22) investigated sail-wing type Darrieus wind-turbines.

Two experimental investigations of sail-type Savonius wind-turbines have recently been reported in the Netherlands (Ref. 23) and in India (Ref. 24). These both present design and experimental data for "almost rigid", constant-sail-profile rotors. Although sail-type vertical-axis wind-turbines had previously been investigated, they were not of the form proposed here — i.e. with a variable sail profile. This novel feature was expected to increase significantly the power harnessing capabilities and so deserved further study.

1.2.3 Theoretical Analysis Of Wind-turbine Flexible Sails

There are considerable theoretical analyses of propeller-type bladed rotors, (Refs. 25 and 26). Data regarding the aerodynamic properties of wind-turbine flexible sails are virtually non-existent although Marchaj (Ref. 27) and Kay (Ref. 28) report some aerodynamic data for triangular yacht sails, but to what extent these can be applied to wind-turbine flexible sails is arguable. An attempt is made in Chapter 7 to use the theoretical work with yacht sails to describe wind-turbine flexible sails.

INTRODUCTION

Literature review

1.2.4 Positive Displacement Pump

A low cost wind-driven peristaltic-type pump has been investigated previously (Ref. 29), but the project was terminated midway, due to other more pressing priorities. There is no formal report of the project. The pumps described in Chapter 10 are (i) a commercially-available peristaltic pump to which modifications are proposed; and (ii) a low technology version of a novel peristaltic pump.

1.3 PROPOSED RESEARCH

It thus appeared that a comprehensive study of sail-type wind-turbines was required. In particular to investigate:-

1. their potential as prime movers to drive water pumps in developing and developed countries;
2. the development of a theoretical analysis of their performance; and
3. their power harnessing augmentation.

CHAPTER 2

THE EVOLUTION OF WIND-TURBINES: AN HISTORICAL REVIEW

2.1 EARLY DEVELOPMENTS

The origin of the wind-turbine is obscure. Speculation implied the presence of wind-rotors in classical Greece, Babylonia, early Gaul and Saxon England, but no references to wind-powered machines exist in reliable records of the ancient and medieval periods (Ref. 30). Probably, windmills and wind-pumps were unknown to the Greeks and Romans (Ref. 31). However, Heron of Alexandria (Ref. 32) referred in the "Pneumatica" to an anemurion (i.e. a wind-vane). According to interpretations, traditional since the sixteenth century A.D., an apparatus consisting of a horizontal-axis wind-rotor driving a piston or air pump attached to a musical organ was described. But Schmidt (Ref. 33) after translating an ancient manuscript, containing the original diagram of the apparatus, with the usual Greek reference letters, records only the musical organ. Vitruvius, within two hundred years of Heron's death, reviewed comprehensively the mechanical devices known at that time (Ref. 34). He mentioned watermills, water-raising wheels, water organs and hoisting machines. He also discussed winds, specifically outlined the behaviour of wind-vanes and referred to the production of organ sounds by the use of air forced under pressure. But no mention was made of wind-pumps, windmills or other sail or vane-operated mechanisms. Not surprisingly, therefore, as neither Vitruvius nor apparently any other classical engineer of the Hellenistic period referred to wind-rotors, there has been a tendency to doubt that Heron's windwheel existed. However there is no reason to dismiss it altogether, but it is probable that Heron's rotor was no more than a hand-held toy (Ref. 35) that failed to develop further at that time.

There are two other prevalent uncertainties concerning the origin of the wind-turbine. The first, mentioned by Clarke (Ref. 36) whilst discussing an ancient Hindu book (Ref. 37) implied that windmills were commonplace circa 400 B.C. But Law (Ref. 38) in translating the "Arthashastra" of Kautilya, referred only once to water being raised via contrivances worked by the wind. Secondly Flettner (Ref. 39) suggested that the Babylonian ruler Hammurabi (circa 1700 B.C.) planned to use wind power in his proposed ambitious irrigation schemes. However there do not appear to be any corroborating records stating whether construction of this system was even started. Nor are there any other references to the development of the wind-turbine during those eras.

HISTORICAL REVIEW OF WIND-TURBINES

Early developments

Vertical-axis wind-rotors probably originated around 200 B.C., in the Sistan region of Iran, near the border with Pakistan (Refs. 31, 35, and 40). This is sandy, arid country, renowned for its persistent high winds. These rotors were shrouded by circular walls, that contained vertical access gaps, some of which were covered up temporarily according to the wind direction. The walls thereby acted as a converger or shroud, usefully constraining the wind to impinge upon the sails or vanes.

There are numerous conflicting accounts of how windmill and wind-pump technologies were propagated from their probable origins in Persia. Some of this contagious conveyance of knowledge occurred via merchants overland, as well as by sailors and merchants through the ports (Ref. 41). In this way the use of wind energy for pumping and grinding reached Islam, India and China in the tenth or eleventh centuries A.D. and North America during the sixteenth century.

Considerable differences of opinion have also been expressed as to why and how the eastern "vertical-axis" wind-turbines were adapted to become the traditional European "horizontal-axis" wind-rotors of the twelfth century A.D. It is possible that the traditional large Persian panemone was modified to suit the more intermittent winds of Europe, so leading to the production of horizontal-axis turbines. However, Wailes (Ref. 42) believed that the European windmill evolved from the Roman horizontal-axis waterwheel, which itself developed from the Greek vertical-axis waterwheel. He considered that the innovative step from the Roman horizontal-axis waterwheel to the familiar European horizontal-axis windmill to be easier than that from the Greek vertical-type. However Horwitz (Ref. 43) suggested that wind-turbines evolved from the Tibetan revolving bookcases (i.e. prayer wheels), which were rotated by vertical-axis waterwheels.

The Domesday survey of Britain, undertaken during the period A.D. 1080 to 1086, refers to several hundred mills, but neither water, wind, oxen nor any other types were differentiated. Thus, it is logical to assume that, because no form of wind-rotor is specifically mentioned, wind was not a harnessed common power source at that time in Britain.

Knowledge of windmills also arrived in Europe either as a result of the first Crusade (Ref. 44) the third Crusade (Ref. 45) or via Russia and Spain (Ref. 46). The first authenticated references to the existence of windmills in Europe were written during the twelfth century. These include the well-documented case of the illegal building of a windmill by Dean Herbert on his glebe lands at Bury St. Edmunds. It was pulled down by order of the Abbot Samson and is recorded in the Chronicle of Jocelyn de Brakelond (A.D. 1191) (Ref. 47). This was long believed to be the earliest record of a windmill in Europe, but White (Ref. 48) found references to five slightly earlier windmills built at Arles in 1162, Normandy in 1185, Provence in 1185, Yorkshire in 1185 and Suffolk in 1187.

HISTORICAL REVIEW OF WIND-TURBINES

Early developments

Records of thirteenth century Europe are replete with references to the use of the then novel contrivances of the windmill or wind-pump. A century later, they were so commonplace that numerous miniatures and illuminated manuscripts of the Bible were depicting windmills in early Hebrew landscapes.

By the fourteenth century, Dutch engineers had taken the lead in initiating windmill and wind-pump design improvements. Wind-powered machines were used extensively for draining marshes in the Rhine delta. Between 1608 and 1612, the Beemster Polder (which is 3 m below sea-level) was drained by 26 wind-driven pumps each of approximately 370 kW.

Although the majority of wind-turbines in Europe were of the horizontal-axis type, there were also many vertical-axis designs, built from the sixteenth century onwards. They were generally based on the early Persian and Chinese wind-rotors, and used for a variety of pumping and grinding applications (Refs. 49 and 50).

During the mid-1700's, Dutch settlers brought wind-energy technology to North America. By 1750, there were approximately 10 000 wind-powered machines in the United Kingdom and about the same number in Germany, 8 000 in The Netherlands and 5 000 in Denmark, but the numbers rapidly declined as coal-fired steam engines became common.

In 1759, John Smeaton (Ref. 51), described a series of experiments with model windmills and watermills, and set out clearly some fundamental principles underlying their designs and performances. His tests led to improved efficiencies of windmills and wind-pumps and laid the foundations for an aerodynamic theory of wind-turbines.

Towards the end of the nineteenth century, in the U.S.A. and Australia, multi-vane wind-rotors achieved widespread adoption in order to drive pumps for stock and crop watering. These rotors were originally developed in France and differed from the familiar rotors of the period in that the usual small number (typically four but exceptionally two, five or six) of large sails were replaced by large numbers (for instance up to 160 on a 5 m diameter rotor) of wooden or sheet-metal blades. These were arranged radially around a shaft to form a wheel of between 3 and 6 m diameter and were usually slightly concave on the windward side. Factory-produced multi-vane machines generally had twenty-four blades, forming a 2.5 m diameter wheel with solidity ratios of approximately unity and tip-to-wind speed ratios of about 2.5. The multi-vane type wind-turbine starts readily in low speed winds and develops a relatively high torque, so it is ideally suited to water pumping — small quantities of ground water being pumped through relatively large heights to elevated tanks, for example, for the subsequent intermittent watering of cattle. The use and manufacture of systems of this type have gradually spread to many parts of the world, notably Australia, North America, South Africa, South America and have been exported from the U.S.A. and Australia to developing countries.

HISTORICAL REVIEW OF WIND-TURBINES

Early developments

During the first half of the twentieth century, as a result of the reorganisation of the flour-milling industry, the old wind-driven corn mills fell into disuse. Large-scale centralised operation replaced the multiplicity of small independent plants, so leading to a decline in the use and technology of wind-powered systems.

2.2 TWENTIETH-CENTURY WIND-POWER UTILISATION

2.2.1 Horizontal-axis Wind-turbines

The first modern wind-turbines designed specifically for electricity generation were constructed in Denmark to meet the demand for rural electrification. La Cour was in charge of the windmill experimental station established by the Danish State at Askov in 1891 and he worked there until his death in 1908. The research was aimed at the improvement of rotor performance and the economic production of electricity via wind-powered machines. The wind-turbines were fitted with plane slatted blades, with a swept area of up to 23 m in diameter supported on steel lattice towers 23 m high and had power outputs of between 5 and 25 kW. The machines were usually coupled to d.c. dynamos, although La Cour also used energy derived from the wind to electrolyse water thereby giving off hydrogen which was burnt to illuminate his laboratory.

By 1910, several hundred such machines were supplying electrical power to villages around Denmark. They were equipped with 100 to 300 Ampere-hour capacity storage batteries, so enabling the wind machines to meet high demands for up to 10 consecutive windless days.

After World War One, Fales (Ref. 52), in the U.S.A. proposed the use of blades with aerofoil sections for use in horizontal-axis wind-turbines. Most large-scale wind-rotors designed since then have followed this pattern, and so achieved significant improvements in their power coefficients.

During the 1920's, Kummé (Ref. 53) in Germany, designed a six-bladed wind-rotor with complex guying, connected to a vertical shaft, with the then novel idea of placing the generator at the base of the tower (i.e. on the ground). But the advantages so gained were outweighed by the tendency of the rotor to "walk around" the horizontal bevel gear at the top of the tower, so throwing the rotor "out of the wind".

In 1929, the French Engineer Darrieus (who had already patented the vertical-axis rotor, which nowadays commonly bears his name (Ref. 54) designed a two-bladed horizontal-axis 20 m diameter, 150 kW d.c. wind-turbine. It required a 20 m high tower and gave a maximum power coefficient of 0.347 at its rated wind speed of 6 ms⁻¹.

Under the direction of Kranovsky in the 1930's, the U.S.S.R. undertook an extensive wind-energy research programme. The largest turbine developed was that built at Yalta on the Black Sea in 1931. This was a three-bladed rotor, 30.5 m in diameter with a 30.5 m high tower. Its rated power was 100 kW in an 11 ms⁻¹ wind, giving a maximum

HISTORICAL REVIEW OF WIND-TURBINES

Twentieth century utilisation

power coefficient of 0.162. It was the first wind-powered system to be connected to an existing power supply network: it was coupled via a 6.3 kV power line to the 20 MW, peat-burning, steam power station at Sevastapol, 20 miles away. Although the design was relatively simple — the blade surfaces were made of roofing material and the main gears of wood — during one year, it achieved an output of 279 000 kWh. The generator and the controls were located in the centre-body housing and regulation was via blade pitch-control. Wind thrust on the tower structure was absorbed by the inclined strut, the lower end of which rested on a carriage, which itself was confined to move on a circular track. This system enabled the rotor to turn automatically into the wind. The Yalta wind-turbine operated for ten years until it was destroyed during the Second World War. Also in the 1930's, the Soviet Union considered the construction of a 5 MW wind-turbine, but this was never implemented.

In the U.S.A. during 1934, Putman (Ref. 55) presented a design for a wind-powered electricity-generating plant, to the S.Morgan Smith Company of York, Pennsylvania. The company manufactured controllable-pitch hydraulic turbines and were anxious to diversify: a logical expansion was into wind-turbines. They agreed to fund the project and to couple the system to the existing Central Vermont Public Corporation Supply Services. After 50 sites had been evaluated it was decided to site the machine on the 610 m high hill (Grandpa's Knob) in the Green Mountains, 10 miles from Rutland. A number of engineers and several universities participated in the design, which resulted in the construction of a two-bladed, 53.3 m diameter rotor mounted upon a 33.5 m high tower. The blades (stainless-steel ribs covered by a stainless-steel skin) weighed approximately 8 tonnes each and adjustable pitch control was employed to maintain a rotational speed of 28.7 r.p.m. The rotor was designed to operate in wind speeds of up to 33 ms^{-1} . At wind speeds greater than this, the blades were feathered and the machine shut down. The wind-turbine turned an a.c. synchronous generator and was rated at 1 000 kW in a wind speed of 13.4 ms^{-1} (giving a power coefficient of 0.369). The output was 2 300 V, 3-phase, 60 Hz and was transformed to 44 kV and fed into the Vermont power lines. The turbine was capable of producing 1 250 kW, but a main bearing failure in 1943 resulted in a two-year delay while waiting for a replacement — because of the low priority given to the project during war-time. It was operational again in 1945, but after a few months, a known weakness (which could not be rectified due to war-time material shortages) resulted in an over-stressed blade failing. The wind-turbine had operated intermittently for a total running period of 1 000 hours. Although the project was considered to be a technical success, economically it was a failure and so the project was stopped and the rotor dismantled.

After World War Two, widespread interest arose in the potential use of wind energy. The main reasons for this were:-

1. fuel shortages and the increasing demand for electricity;
2. the supposedly high and rising costs of electricity generated from steam-driven plant;

HISTORICAL REVIEW OF WIND-TURBINES Twentieth century utilisation

3. the economic and political problems of post-war years encouraged countries to become more dependent upon indigenous power resources;
4. the realization that fossil fuel reserves were finite; and
5. an increasing knowledge of aerodynamics.

This resulted in the Electrical Research Association (E.R.A.) of the U.K., developing an extensive wind energy research programme from 1945 to 1960. Although several medium-scale (~ 100 kW) wind-turbines were built, the majority of the studies concentrated upon site selection and comprehensive wind mapping of the United Kingdom. In 1955, a 100kW wind-turbine designed by the French engineer Andreau (Ref. 56), was constructed by Enfield Cables on a test site at St. Albans. This was a 2-bladed (aluminium alloy), 24 m diameter machine on a 3.5 m tower: it was rated at 100 kW in a 13.4 ms^{-1} wind, giving a power coefficient of 0.144. Air, rather than gears, was used to transmit the propeller power to the generator. The blades were hollow and, when rotated, they acted as centrifugal air pumps. Air entered ports in the lower part of the tower, passed through a vertical-axis turbine which turned an electric generator and was exhausted through the tips of the blades. Unfortunately large friction losses ensued in the internal air duct of the machine, so reducing the advantage achieved by the elimination of the mechanical coupling. This resulted in a relatively low power coefficient. On completion of the feasibility tests at St. Albans, the British Government withdrew their support for the project, in the face of objections to its permanent siting on the summit of Mynydd Anelog, Caernarvonshire. Thus the machine was sent to Algeria, where it ran satisfactorily until 1961.

During 1955, a 100 kW wind-turbine (built by John Brown Engineering) was constructed on Costa Hill in Orkney. It was rated in a wind speed of 16 ms^{-1} and coupled to the local diesel-powered electricity network. However it was soon shut down due to operational and maintenance problems.

The 1950's was a period of relatively intense research into the behaviours of wind-turbines, especially with respect to their development for electricity generation, i.e. by employing wind-turbines with high tip-to-wind speed ratios. However sail-type wind-turbines were also considered (Ref. 57), but despite several advantages (such as economic construction and self-regulating behaviours in high wind) they were not comprehensively investigated because of their inherently low tip-to-wind speed ratios.

A number of 3-bladed wind-turbines were manufactured by Dowsett Engineering in the early 1960's. They had hydraulically-operated pitch-controlled blades and were rated at a wind speed of 11 ms^{-1} . Twin fan-tails were used to turn the rotor into the wind and the machines had tower heights of 10 m.

HISTORICAL REVIEW OF WIND-TURBINES

Twentieth century utilisation

Also in the early 1960's, a 3-bladed 100 kW wind-turbine was constructed on the Isle Of Man. It was rated at the relatively high wind speed of 18.4 ms^{-1} and the pitch of the extruded aluminium blades was fixed in order to reduce construction costs. The rotor was designed to run at a constant rotational speed driving an induction generator connected to the local electricity grid. To prevent over-speeding in the event of the electrical load being "lost", spring-loaded centrifugal air brakes were fitted to the blade tips. The Isle Of Man machine operated successfully for several years and it was claimed to produce electricity at an economic price (Ref. 58). However the project was discontinued because Britain was embarking upon a major nuclear-energy programme and it was then believed that the power so produced would be both plentiful and cheap.

In the U.S.A. during the late 1940's, Thomas, an engineer with the Federal Power commission, analysed wind-turbine data from the "Grandpa's Knob" project. Although many designs for large rotors were proposed, not even one was constructed.

In continuing their research, the Danes developed a 3-bladed 24 m diameter, 200 kW machine with a tower height of 26 m (known as the "Gedser" wind-turbine). This was constructed by the F.L. Smidth Company and, when operated at its rated wind speed of 15 ms^{-1} , gave a power coefficient of 0.205. It used an electric motor to turn the rotor into the wind and the blade pitch was fixed, except for the tips which pivotted to regulate the rotational speed in strong winds. It was connected to the Danish power supply system and produced approximately 400 000 kWh per year between 1959 and 1967. The "Gedser" wind-turbine ran successfully until 1968, when the expansion of the rural electrification network made it financially uneconomic for it to remain operational.

In Germany, Hutter, who made substantial contributions to the design of wind-turbines, developed light-weight constant-speed rotors which were controlled by varying the pitch of the propeller blades. They had glass-fibre bladed rotors attached to simple hollow-pipe towers supported by guy ropes. The largest was 15 m in diameter and rated at 100 kW in an 8 ms^{-1} wind: it ran for 4 000 hours at full rated power, between September 1957 and August 1968.

Electricité de France built three large wind-turbines in the late 1950's and early 1960's (Ref. 59). One had a 21 m diameter rotor rated at 130 kW in a wind speed of 12.5 ms^{-1} . There was also an 800 kW version of the 1929 Darrieus design rated in a 17 ms^{-1} wind. The third to be built was a 1 000 kW three bladed rotor, also rated in a 17 ms^{-1} wind.

2.2.2 Vertical-axis Wind-turbines

During the 1920's, the French engineer Darrieus filed a patent referring to "a turbine having its rotating shaft transverse to the flow of the current". This patent (Ref. 54) covered various configurations of vertical-axis wind-turbine. His preferred design, was for three vertical aerofoil sections, connected to two end-plates,

HISTORICAL REVIEW OF WIND-TURBINES

Twentieth century utilisation

with a shaft running vertically through their centre. All the designs were for operation at high tip-to-wind speed ratios. He also stated that the blades may be rectilinear and parallel to the central shaft, or, in order to reduce the bending stress on the blades, they could be curved or twisted similar to a skipping rope, approximately in the form of a semi-circle. Darrieus also worked on various horizontal-axis wind-turbines, but despite a comprehensive literature search, no record was found as to whether a large scale vertical-axis wind-turbine was actually built at that time. The concept, therefore, lay dormant for almost half a century until the National Aeronautical Establishment of the National Research Council of Canada independently re-invented and developed a vertical-axis wind-turbine (Ref. 16) (only discovering the 1926 Darrieus patent when they tried to file their own). The NRC Darrieus-type wind-turbine consisted of three aerofoil sections bowed out in the form of a troposkien. That is, the blades were shaped to fit the profile that a perfectly flexible cable of uniform density would assume, if spun about a vertical-axis.

Also during the nineteen-twenties, the German engineer Flettner, patented what subsequently became known as the Flettner rotor (Ref. 39). This consisted of a large vertical or near vertical-axis cylinder, which, if rotated (for example by a diesel engine) in the presence of a wind, would be acted upon by a horizontal or near horizontal lateral thrust. The thrust, caused by the asymmetrical streaming of the wind, is known as the Magnus effect (after the German Professor, who was the first person to undertake its systematic investigation (Ref. 60). Flettner used the rotors to propel ships and also proposed a four-bladed horizontal-axis wind-turbine, with the conventional blades being replaced by Flettner rotors. But again, despite an extensive literature search, only two subsequent references (Refs. 61 and 62) to this novel wind-rotor were found since Flettner's original design. Although the rotor method of ship propulsion was relatively inexpensive, the higher speeds and better reliabilities achieved with normal screw propulsion systems, resulted in the Flettner rotor not coming into common use, though recently there has been a resurgence of interest in it.

Savonius, recognised that it was feasible to harness the wind in order to maintain the Flettner cylinder rotating, (Refs. 13 and 63) and thereby to dispense entirely with the need for auxiliary power for this purpose. Savonius modified the Flettner design by splitting the rotor in half: the two semi-cylindrical surfaces were then displaced sideways along the plane of the cut, thereby forming a wind-turbine, which in cross-section resembled the letter S. A gap between the turbine's semi-cylindrical cups was allowed, such that some of the air striking one cup would flow through the central gap, and so provide a useful thrust on the other cup. This also resulted in a reduction in the overall drag, because the air pressure downstream of the rotor was higher than if there were no central gap. The speed of rotation was also greater. The Savonius rotor developed larger lateral (i.e. propulsive) forces than could be obtained with a comparable sized Flettner rotor. However the Savonius rotor has survived despite, rather than because of, these lateral forces. This design has been used successfully for centrifugal ventilators, aero-turbines for pumping liquids, as well as for harnessing tidal power and for measuring ocean currents as low as 0.5 knots. Savonius rotors have

HISTORICAL REVIEW OF WIND-TURBINES Twentieth century utilisation

also been used as an addition to Darrieus rotors in order to enable them to be self-starting. They were used in the Flettner four-bladed windmill proposal (Refs. 39 and 62): to the ends of each of the four Flettner rotors it was planned to attach smaller Savonius rotors with end-plates, in order to achieve self-starting.

Madarasz adapted Flettner's rotor concept to generate electricity via 18 rotating cylinders moving (on trolleys) around a 457 m diameter continuous track (Ref. 64). The train of Flettner rotors generated the Magnus effect, so propelling the rotating cylinders around the track. The rotors, each 27 m in height and 6.8 m in diameter, were designed to produce up to 18 MW of electrical power at a track speed of 8.9 ms^{-1} in a wind of 13 ms^{-1} . In order to maintain continuous electricity generation, the rotors had to reverse their direction of rotation every half revolution round the track. A full-size rotor of this design was constructed and tested at Burlington, New Jersey, in 1933. When the test rotor blew down in a strong wind, the six public utility companies sponsoring the project withdrew their further financial support and the concept was abandoned. Recently such a system has again been proposed (Ref. 65) and the costs per kW output are said to compare favourably with those for large scale horizontal-axis wind-turbines.

The majority of pre-1970's research and development projects concerning the utilisation of wind energy were technically successful, but failed to lead to commercial exploitation. There were two main reasons for this:-

1. Throughout the post-war period, 1945-73, fossil fuels were relatively inexpensive and, relative to the Retail Price Index for other commonly used goods, they became progressively cheaper. Although wind-turbines have a "free" energy source, the costs of the power so harnessed is determined by the amortised cost of the machine and, to a lesser extent, by the maintenance and running costs. Before 1973, experience indicated that electricity derived from the wind would be more expensive than that obtained via the combustion of coal, town gas or oil.
2. During the 1950's and 60's, it was confidently expected that the production of electricity by nuclear fission would provide abundant supplies of cheap electrical energy.

2.3 POST 1973 AND FUTURE DEVELOPMENTS

Because of economic and safety reasons, nuclear power is no longer seen as the only solution to our energy problems. This together with the sharp rises of unit oil price of 1973 and subsequently, caused difficulties for many countries. These two factors taken together made some politicians realise at last, the finite extent of the world's fossil-fuel reserves, and resulted in the more enlightened governments investing in research programmes aimed at harnessing ambient energy.

HISTORICAL REVIEW OF WIND-TURBINES

Future developments

During the 1970's, wind-turbine research and development programmes were initiated in the more developed countries. Despite the overall sizes of the associated research budgets being extremely small compared with those allocated for nuclear energy research, significant advances were made.

In the United Kingdom, wind energy as a potential power source for generating electricity was evaluated by the Energy Technology Support Unit of the Department of Energy. This was part of a broader examination of the potential of alternative sources of energy and the resulting publication (Energy Paper No. 21) described the prospects for wind energy in the U.K. Following this, a limited research programme was instigated concentrating almost exclusively on Department of Energy or Science and Engineering Research Council funded studies of large-scale electricity-generating machines. These programmes are well documented and are summarised by Millar (Ref. 66).

During the 1970's, wind-turbine research expectations were that large multi-megawatt scale rotors would offer lower energy costs than smaller (say 15 to 20 m diameter) turbines. However, recent research (Ref. 67), suggests the contrary viewpoint — namely that more medium-sized wind-turbines could harness, during the same period the same amount of wind energy less expensively. Additionally, demand for multi-megawatt systems is somewhat limited to large electricity utilities and, especially in the United Kingdom, there is a lack of a sufficient number of acceptable sites for such large wind-turbines. Medium-sized wind-turbines are less subject to these constraints and thus have a far greater market potential. Wind-turbines of 10 to 20 m diameter have pay-back periods of 6 to 9 years (Ref. 67), (even without any government subsidy or tax incentive), when operated in parallel with an existing electrical grid system. Thus the potential for smaller wind-turbines is being realised. Indeed, relatively small-scale (~ 10 m diameter) propeller-type, horizontal-axis wind-turbines, when grouped together in "farms", are (especially with the assistance of tax incentives) currently generating electricity profitably in many parts of the U.S.A.

Most "western" countries, with the notable exception of the U.K., now have an established manufacturing base for small-scale wind-turbines. These have a growing market in rural areas, where the present costs of energy are relatively high. This is one of the wind-turbine's traditional markets. In this context it should be remembered that wind power was partly instrumental in the development of the "wild west" and "outback" in the U.S.A. and Australia respectively. "Wind-pumps" were primarily used for crop and stock watering and a considerable "replacement market" still exists there for these wind-turbines. The developing countries offer a vast prospective market for water-pumping equipment. Appropriately-designed wind-turbines do not present the same technological problems as other systems (e.g. photo-voltaics) for solar energy conversion and are readily accepted in the community, particularly if they are manufactured and maintained locally.

HISTORICAL REVIEW OF WIND-TURBINES
Future developments

Considerable interest is also being expressed in producing relatively reliable and maintenance-free turbines (with battery storage) for powering remote repeater stations for telecommunications. Whilst the reliability and maintenance aspects still give rise to concern, a favourable market does exist, because the costs of alternative power sources are relatively high.

Thus the future development of wind-turbines looks assured — especially if sufficient "pump priming" government funding (particularly for small systems) is forthcoming. This would lead to a strong home market demand, thereby developing Britain's manufacturing capability and hence leading to a lower unit cost and consequently to a greater ability to compete in export markets.

CHAPTER 3

SAIL-TYPE WIND-TURBINES

Flexible-sail wind-turbines are lighter in weight than the rigid, horizontal-axis multi-vane and the metal-vaned vertical-axis types of wind-turbines. The sail profile is determined by the wind. They are cheaper to construct and they can be readily fabricated by semi-skilled labour using a variety of indigenous skills and materials in Third World countries.

3.1 FLEXIBLE SAILS

The sail wind-turbine is unique in that the wind shapes the sail profile. This enables them to have varying sail profiles dependent upon wind strength. Sail-type wind-turbines are self-starting and, when used with elastic sail attachments, self-regulating in high speed winds — although the sails should be furled during (infrequent) excessively high winds. They are inherently slow running (with optimal tip-to-wind speed ratios of approximately unity) and have large solidity ratios and high starting torques, so readily overcoming the relatively large torques required to start the majority of irrigation pumps.

The flexible sails were considered because of the following major attributes;

1. self-starting capabilities: a relatively high torque is produced at low rotational speeds;
2. useful power is harnessed even from very low speed winds;
3. the sails provide a degree of self-regulation — when used with elastic sail attachments, they "spill the wind" at high speeds, so only needing to be furled during the infrequent, excessively-high winds; and
4. the sail profile is determined by the strength and direction of the wind so it does not possess a constant sail profile, as with the more conventional wind-turbines

The greater the number of sails or blades implies lower tip-to-wind speed ratios and higher developed torques. A wind-turbine with few blades attains higher rotational speeds (and hence

SAIL-TYPE WIND-TURBINES

Flexible sails

tip-to-wind speed ratios) but generates a smaller starting torque than a correspondingly sized high solidity wind-turbine. Slow speed sail-type and multi-vane type wind-turbines are thus suitable for driving water pumps and high speed propeller-type rotors for generating electricity. For low tip-to-wind speed ratio wind-turbines, the large number of sails (or blades) compensates for the reduction in the power harnessed due to drag.

3.2 HORIZONTAL-AXIS WIND-TURBINES

The horizontal-axis sail-type wind-turbine is typified by those commonly found on the Aegean islands. Their origin is obscure, but they probably evolved because of the local knowledge and experience with sailing ships. The recent resurgence of interest in the sail wind-turbine has occurred because of its cheapness, design simplicity and ease of construction and repair using indigenous materials, by local semi-skilled labour. Its other major advantage is the ability to produce worthwhile power outputs in relatively low speed ($\sim 5 \text{ ms}^{-1}$) winds. There are still many in use today, the highest densities being on the plain of Lassithi in Crete and the coastal plain of Chachoengsae Province in Thailand.

There are several variations of the horizontal-axis sail-type wind-turbine but the basic form is similar to that of the Cretan-type.

3.2.1 Cretan

This design consists of a near-horizontal shaft with six to ten radial arms so that the attached sails are inclined into the oncoming wind (see Fig. 1).

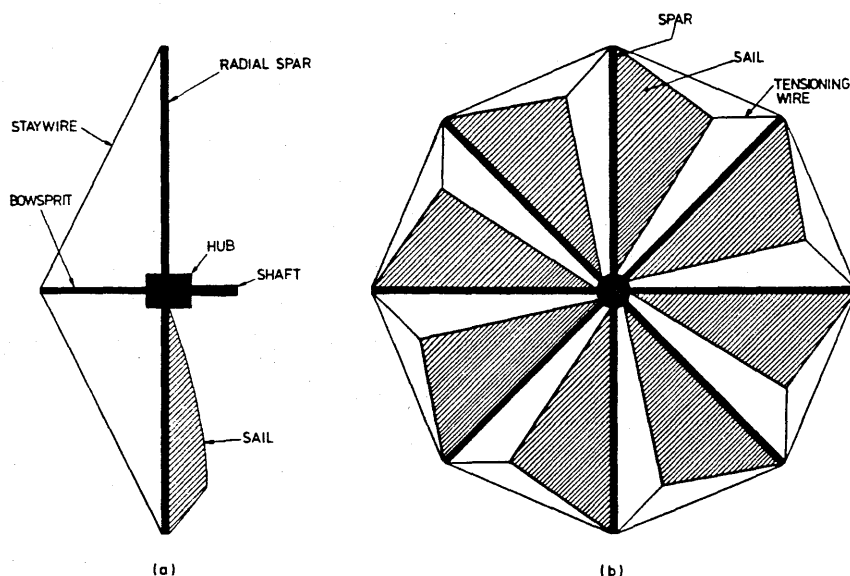


Fig. 1. Basic features of the traditional "Cretan" type wind-turbine.

SAIL-TYPE WIND-TURBINES

Horizontal-axis

Adjacent arms are tied to each other at the tips and carry the triangular sails between them. The whole structure is supported by wires connecting the arm tips to the bowsprit (a nautical term for the forward extension of the shaft).

The rotors are generally 5.4 m in diameter and are supported by a lattice steel tower, that has replaced the traditional stone tower. These stone tower structures used to incorporate the corn grinding equipment, but nowadays the wind-turbines are used almost exclusively for driving water pumps.

In Crete, during the season when irrigation is desirable, gentle breezes tend to occur and these will not threaten the structural integrity of the wind-turbine. Due to the ability of these flapping sails to be shaped into aerofoils by the wind, the Cretan wind-rotor is self-starting and because the sails are self-feathering, it rarely acquires excessively high rotational speeds. Nevertheless if gale force winds have been forecasted, then the sails are usually furled.

The sail type wind-turbine (a low initial capital-cost wind-rotor) (Ref. 1) is still in common use in many countries. This indicates its economic viability even during the recently ended era of cheap energy. Thus the main attractions of such a design are its simplicity and low cost despite its relatively intermittent output.

3.2.2 Thai

These 6 m diameter cloth or bamboo sail wind-turbines are usually used for brine pumping — some are said to have been operating for more than two generations, employing manual, quick-release self-feathering devices (Ref. 3). Unlike the traditional Cretan-type wind-turbines, they work in a wind regime where the wind emanates from two different directions only. Therefore there is no need for self-orientation, so the capital cost is appropriately reduced.

3.2.3 Madurai

An adaption of the Cretan-type rotor, this slightly larger (10 m diameter) wind-turbine has 8 canvas sails and drives variable stroke reciprocating pumps. Developed in India, (Ref. 3), it makes maximum use of local materials and skills.

3.2.4 Omo

The Intermediate Technology Development Group constructed several 6 and 8 sail rotors (and also a metal-vaned Savonius-type) in Ethiopia at the Omo river mission (Ref. 5). These horizontal-axis sail rotors are said to have proved to be more efficient than commercially imported multi-vane wind-turbines, whilst the performance of the rigid-vaned Savonius rotor was said to be relatively poor.

SAIL-TYPE WIND-TURBINES

Horizontal-axis

3.2.5 N.A.L.

During the 1960's the National Aeronautical Laboratory (N.A.L) at Bangalore, India, constructed many multi-vane rotors (referred to as WP-2's), but these were relatively unsuccessful. Larger 10m diameter sail-type wind-turbines were developed in the 1970's. These were less expensive than the WP-2's and pumped significantly greater quantities of water using a swinging-vane rotary pump (Ref. 6).

Technical, performance and economic data (taken from Ref. 68) for these and other similar wind-turbines are presented in Appendix B.

3.3 VERTICAL-AXIS WIND-TURBINE

Although the vast majority of vertical-axis wind-turbines have metal or wooden vanes, there are traditional as well as more modern sail rotors.

3.3.1 Chinese

The Chinese wind-turbine is the earliest form of variable sail profile vertical-axis rotor. They dispense entirely with the shield walls as used in the early Persian designs (see Chapter 2, section 2.1). This is achieved by adapting the fore-and-aft rig of the Chinese junks to the wind-turbine sails (see Fig. 2). The sails travel in a horizontal course around a central shaft, where the sails are similar to the main sail on a sail boat.

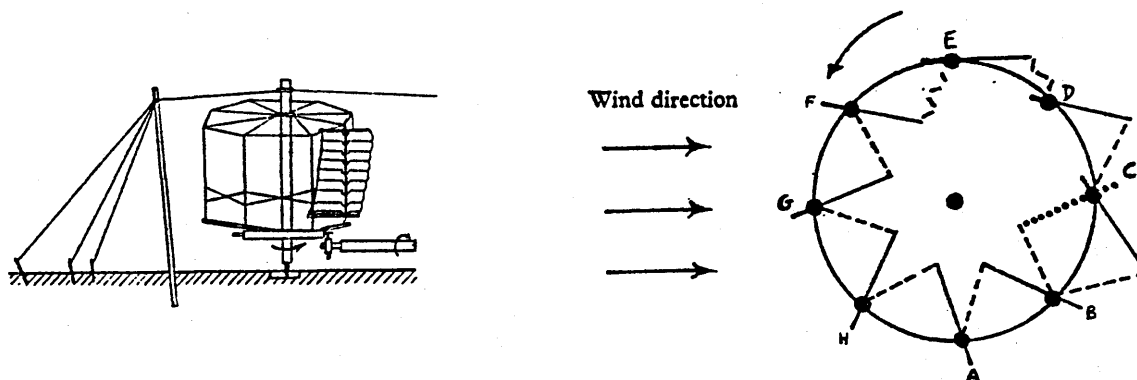


Fig. 2. Traditional Chinese-type vertical-axis wind-turbine.

In position A, the sail is held taught against the wind by its "sheet" rope, but when the sail reaches point C, it is blown outward by the wind. At point E, the sail is offering no resistance to the wind, whilst at point G, the sail has again tightened, preparing for its momentum capture phase of operation at point A. This simple type of vertical-axis wind-turbine was said to still be in operation during the 1960's (Ref. 35).

SAIL-TYPE WIND-TURBINES
Vertical-axis

3.3.2 Campbell Chinese-type Wind-turbine

Campbell (Ref. 20), recently developed a prototype vertical-axis sail wind-turbine, primarily designed for generating electricity. Although it used relatively modern construction techniques and materials, compared with traditional vertical-axis wind-turbines, it is in essence a Chinese-type wind-turbine (see section 3.3.1)

3.3.3 Indian Accademy Of Science (I.A.S.)

This Savonius-type wind-turbine (Ref. 24), consisted of two cloth sails supported by vertical wires attached between each end plate. It was designed to be easily constructed using materials and skills available in rural areas of India. Field tests with the rotor connected to a positive displacement pump indicated reasonable performance and reliability.

3.3.4 Steering Committee For Wind Energy In Developing Countries (S.W.D.)

Again using cloth sails and wooden end-plates, this wind-turbine (Ref. 23), was also aimed at less developed countries as a power source for raising water. As with the I.A.S. system (see section 3.3.3), the sails were used primarily to reduce the weight of the wind-turbine and were held relatively taut, so possessing a constant sail profile with respect to wind direction.

3.3.5 Low Energy Systems

This is a sail-wing type wind-turbine designed to operate in relatively low wind-speeds. Developed by Hurley (Ref. 21), it was constructed about the vertical-axis and used cloth sails. Although the initial design thoughts were to develop a sail-type Savonius wind-turbine, the final design was analogous to the Darrieus-type rotor, see Fig. 3.

During each revolution of the rotor, the sail changes its profile. The wind switches the concave surface of the sail from one side to the other automatically. This enabled the rotor to develop a positive torque, even at low rotor speeds. Another feature was that the trailing edge shifted its position relative to the leading edge during rotation. The trailing edge was deflected to the side away from the wind, due to the wind-filled sail. This is said to have had the effect of reducing the angle of attack of the relative wind, so tending to delay the stalling of the sail.

SAIL-TYPE WIND-TURBINES
Vertical-axis

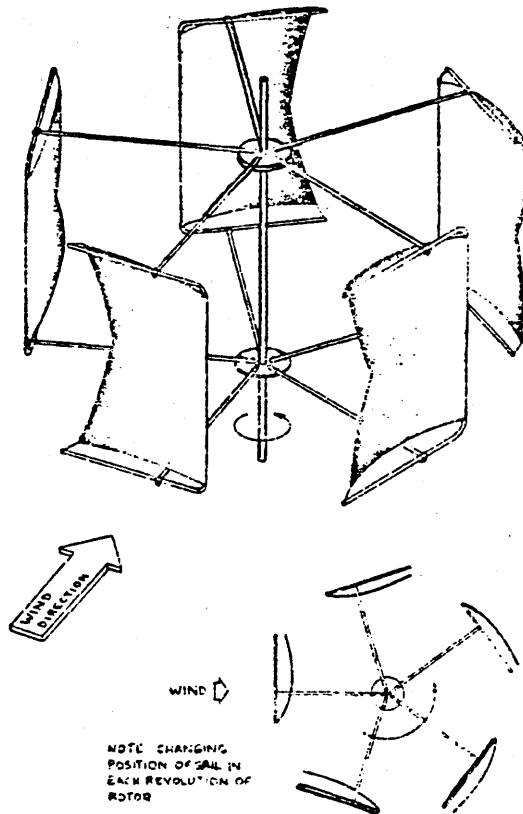


Fig. 3. Sail wind-turbine developed by Low Energy Systems.

The wind-turbine has been used successfully for pumping water and its performance is said to be the same as that of a similar sized horizontal-axis wind-turbine. Recently Hurley's rotor has been further investigated (Ref. 69) for raising water in developing countries.

3.3.6 "Starter Bucket" For Darrieus Rotors

Shankar (Ref. 70) used Savonius wind-rotors with cloth sails as a "starter bucket" for Darrieus-type wind-turbines. The Darrieus-type wind-turbine is not necessarily self-starting, and the Savonius rotor, attached to the Darrieus, facilitated starting.

3.3.7 Sail-wing Darrieus Rotors

Sail-wing Darrieus wind-turbines have been investigated (Refs. 22 and 71). The vertical blade design is similar to that of Hurley (see section 3.3.5) except that the sails do not change their profile relative to the wind direction. The sail-wing is said to have good starting characteristics, better than the metal-vaned rotors, but a

SAIL-TYPE WIND-TURBINES

Vertical-axis

relatively low power coefficient. These sail-wing Darrieus wind-turbines are said to be relatively cheap to construct, easy to maintain and have potential for small-scale applications.

3.4 WIND-DRIVEN WATER PUMP

The major use of sail wind-turbines is for pumping water, an application for which the uncertainties of the winds prove to be less of an embarrassment than the poor dependability of the electricity supplies — rural areas frequently experience long-duration electricity supply interruptions, priority being given to industrialised regions. Because up to 80 per cent of rural electricity is used for pumping (Ref. 72), disruptions in such supplies often lead to crop failures. Employing water pumping wind-turbines reduces the likelihood of this by raising ground water, which exists even in arid areas and has previously remained underutilised due to the lack of pumping power. Short term durations (~ 2 days) of calm weather will still permit wind-driven irrigation to be viable because sufficient moisture will remain near the roots to support crops for this period.

Several less-developed countries have discovered that a reliance upon fossil fuels can create vulnerabilities. For example, it is estimated (Ref. 73) that a shortage of fuel for irrigation pumps in 1974 reduced the wheat harvest in India by one million tonnes. Another example concerns an irrigation pump installed in a Bangladeshi village in 1977. This was only used sparingly because the villagers could not afford the diesel fuel to run it, and so the harvest was considerably reduced.

It is often uneconomic to supply electricity, because the widely distributed population requires that small loads be transmitted over long distances. The World Bank estimated (Ref. 73) that electricity supplies had reached only 12 per cent of rural residents of the Third World by 1971, and that only half of these could afford to purchase the electricity so available. It is expected that the service will expand at a rate of about 1 per cent annually, and so approximately three-quarters of the rural population of the developing world will still be without electricity by AD 2000. Thus because of the frequently occurring lack of electricity and the high unit costs of imported fuel oils, wind-turbines are becoming increasingly used in developing countries.

In the developing world farmers are often very poor and are usually not seeking expensive wind energy conversion systems (such as those commercially available with thirty-year life expectancies). The construction of cheaper units with, say, a five to ten year life span would reduce the investment risk (that a wind-driven water pump may not completely satisfy the conceived requirement) and so be more likely to be adopted.

SAIL-TYPE WIND-TURBINES

Water pumping

Employing wind-turbines to drive water pumps directly (as opposed to generating electricity that is subsequently used to drive a pump) maximizes the use of the wind's energy for pumping. The costs of constructing and running such pumps can be significantly less than conventional electric or oil powered pumps (Ref. 74).

The sail type wind-driven water pump therefore appears to be ready for a much wider acceptance in rural communities and it will not present the same problems of operation and maintenance as with internal combustion engine powered pumps (Ref. 75).

3.5 WIND-DRIVEN WATER PUMP APPLICATIONS

3.5.1 Water Raising In Less-developed Countries

The greatest potential for the slow running, high solidity wind-turbine exists for water pumping. Even in very hot climates there are usually sufficient supplies of ground water, but these are unavailable to farmers during the dry season solely due to the lack of pumping power (Ref. 76). Sail-type wind-turbines could be used to raise water from considerable depths. The main criterion is that the wind-turbines can be manufactured locally in developing countries, using relatively unskilled labour. Often those people who would benefit most from harnessing wind energy are those least able to afford to do so, but in constructing the turbines locally, the major portion of the wealth so spent would help the local community and the manufacturing costs could be kept relatively low.

3.5.1.1 Crop Irrigation -

Many developing countries depend upon hydro-electric power generation in order to meet their electricity requirements, over half of which are for irrigation pumps (Ref. 77). This leaves them susceptible to the vagaries of the weather and a prolonged drought can severely impair productivity and stunt growth, so losing in one season, benefits that may have accrued over many years. The introduction of large sail-type wind-turbines can however, reduce this vulnerability: such rotors would operate even in light winds during the dry months to facilitate the irrigation of crops. Diesel pumps are sometimes used for this purpose but they are expensive because of the relatively high capital and running costs, and the rapidly rising prices of imported fuels. Efficient five horse-power (3.7 kW) electric pumps are being more widely employed as rural electrification proceeds, but only the wealthier farmers can afford them. Bullock-operated pumps remain the most common and reliable source of power for irrigation for subsistence farmers.

Trickle irrigation is sometimes suggested as a great benefit to less-developed countries. Small quantities of water (and also plant nutrients) can be pumped at low flow rates (2 to 10 litres per hour) to the roots of the crops — i.e. in the immediate vicinity of the plant. Although this is advantageous in that it uses less water and

SAIL-TYPE WIND-TURBINES Water pumping applications

reduces transpiration and evaporation losses, it is a relatively expensive irrigation technique inappropriate for the poor population of developing countries. Its major disadvantage is the high cost of implementing such a distribution system. Polythene tubes (12 to 16 mm in diameter) are needed to convey the water to the plant roots and these are susceptible to blockage.

This system is more suited to intensive market gardening where light, controlled irrigation and fertilization are required. A large storage tank would be cheaper and more convenient for the majority of the people in the rural developing world, rather than an extensive trickle irrigation scheme.

With sail-type wind-turbines built from simple commonly-available materials, adequate power outputs to satisfy the need for irrigation power sources are possible. The drawback of wind intermittency can usually be tolerated for crop irrigation, provided sufficient water is distributed when averaged over a three-day period.

Thus sail-type wind-turbines could be profitably employed to raise water for irrigation.

3.5.1.2 Water For Domestic Use -

Water is a basic requirement for any community, especially for domestic applications. Provided storage facilities exist, wind-turbines could simply and cheaply raise water from considerable depths (where there is usually sufficient water all year) and so provide a reliable water supply for domestic purposes.

3.5.2 United Kingdom Applications

3.5.2.1 Irrigation -

The approximate United Kingdom land area is 24 million hectares, of which roughly 18 million is arable land. In the majority of years, over a large part of England and some parts of Wales and Scotland, rainfall is insufficient to maintain potential crop transpiration during crop life. Thus some form of irrigation is often required. These areas of soil moisture deficit experience, on average, less than 90 mm annual rainfall in England and Wales and less than 760 mm in Scotland. Approximately 100 mm of irrigation water will make up this shortfall, even in the very driest years. Thus some form of irrigation power source is required. Diesel or electric pump-sets are traditionally used for this purpose but although the volume flow rates of wind-driven water pumps are significantly less than those of diesel or electric pumps, wind-powered systems are becoming an increasingly viable proposition for the isolated farmer.

SAIL-TYPE WIND-TURBINES

Water pumping applications

Sail-type wind-turbines driving water pumps can cheaply and simply raise small quantities of water for irrigation, or alternatively for storage in elevated tanks for subsequent stock watering. It does not matter that the wind is intermittent — when it blows it just stimulates the pump to "top-up" the tank. The water in the tank will then be able to be used by the farmer when and where required, without further pumping.

Thus wind-driven water pumps should present a modest irrigation source for United Kingdom farmers who need to get away from the need to use increasingly expensive fossil fuels, as well as those employing extensive greenhouse systems requiring regular watering.

3.5.2.2 Boosted Thermo-syphon System -

Solar heating systems would be much more efficient if a conventional electric pump need not be used. For such a system to transfer the heated high effective conductivity liquid, downwards, to where it is needed, consider its energy ratio. This is the total amount of energy obtained from a given system during its lifetime, divided by the total input of energy to that system in order to build, install and maintain it throughout its life. In general, the energy ratio for an electrically driven circulating liquid, solar collecting system — say 2.75 to 1 — is increased to about 10.5 to 1 for the equivalent thermo-syphon system (Ref. 78). Thus, using a wind-driven pump to boost the performance of the thermo-syphon (see Fig. 4) combines the advantages of pumping with reduced energy expenditure of the thermo-syphon.

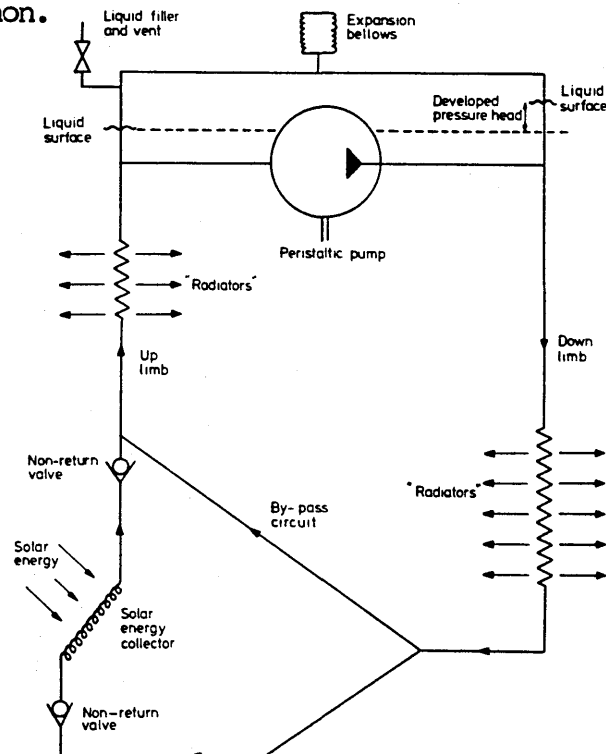


Fig. 4. Schematic representation of the boosted thermo-syphon closed circuit. (Except for the "radiators", all the circuitry is extremely well insulated thermally).

SAIL-TYPE WIND-TURBINES

Water pumping applications

Because only relatively low torques will be generated by wind-turbines of less than 2.5 m diameter, it is suggested that the pump (a peristaltic pump see chapter 10) be used in the rather unconventional, gravitational-boost, manner shown in Fig. 4.

For a full size average British house, the developed pressure head with the 0.64 m diameter horizontal-axis wind-turbine (see Chapter 8) would, for most applications, be too small to induce a sufficiently rapid liquid circulation. Thus a larger rotor, of about 2.5 m diameter, would be more appropriate.

The low volume sealed system consists of two small reservoirs, whose vapour spaces are at identical pressures (preferably atmospheric). The reservoirs are at the tops of the "up" and "down" limbs (see Fig. 4) and connected by the pump which would provide a head of liquid in the "down" limb above that in the "up" limb. The whole system is extremely well insulated thermally, except for the radiators. The solar collector and heating circuit is filled with a low viscosity, high effective thermal conductivity, low vapour pressure, low freezing point liquid. In practice, during winter the solar energy would normally only be used for preheating the liquid and consequently an auxiliary "boiler" would be incorporated in the by-pass circuit.

The wind-turbine would thus replace the electric drive of a commercially available pump. However, an auxiliary electric motor would be necessary to drive the pump during cold weather in the absence of winds.

The peristaltic pumping system would also incorporate a one-way valve which would prevent direct flow from the top of the "down" limb to the top of the "up" limb. However, in the event of, say, large amounts of solar energy, without any wind, the valve would permit natural convection circulation through to the cold limb.

CHAPTER 4

WIND-TURBINES FOR USE IN DEVELOPING COUNTRIES

Wind power in developing countries is becoming increasingly popular. This chapter outlines the appropriateness of flexible sail wind-turbines for driving water pumps and describes their benefits for rural communities in the Third World. The limitations of many "aid" programmes are also outlined.

4.1 INTERNATIONAL PERSPECTIVE

A nation's energy resources (or lack of them) can affect dramatically its wealth and the standard of living of its population. The availability of sufficient energy is vital for the development of any nation, but in many developing countries, a double energy crisis has emerged during the last decade. This is due firstly to the recent rapid increases in the prices charged for crude oil and secondly to the growing shortages in many poor countries of traditional fuels such as wood, so plunging these countries into deeper financial recession.

It is a common fallacy that the energy needs of the Third World are minute compared with those of "the West". This is based solely upon the assessed consumptions of "commercially-supplied" oil and coal, little or no account being taken of the prevalent use of wood, charcoal and animal dung in the poor countries. The natural environment of developing countries is also steadily deteriorating, due to deforestation. A basic principle of success, is to link what you have to what you need. In the present context this means that the developing countries should become more self-sufficient and so less dependent upon imports. Thus attention is now being focused on the harnessing of new and renewable (i.e. non-depletable) sources of energy by low-technology means in those countries. This is not a ploy to halt the development of the Third World, as many of its critics argue, but rather a reasonable approach for those developing countries suffering environmental and/or energy shortage problems.

Fossil fuel reserves are disproportionately dispersed around the world whereas wind energy, though diffuse, is much more uniformly distributed. Thus wind, (as a power source) favours neither the rich nor the poor countries, i.e. neither the developed nor the less-developed nations. So, provided the technology for harnessing such energy resources is relatively simple, such a renewable resource possesses great potential for use in developing as well as developed countries.

WIND-TURBINES FOR DEVELOPING COUNTRIES

International perspective

Therefore wind power has become increasingly recognised as a major contributor to the future development of the Third World. For example United Nations conferences and expert working groups have, for several years, been discussing and outlining the benefits of supplying cheap, simple, wind-driven water pumps for the rural poor (Refs. 3 and 79). However even greater benefits will ensue from wind energy turbines if they are of simple design so that they can be manufactured (and repaired) locally with indigenous materials thereby creating "at home" employment. This reduces the need for available foreign currency and thereby does not contribute to negative balance-of-payments problems for the poor countries.

4.2 AID PROGRAMMES FOR LESS-DEVELOPED COUNTRIES

Table 1
Aid given to developing countries during 1980.
(Based upon DAC Chairman's report, 1981).

<i>Donor nation</i>	<i>Total amount (10⁶ US \$)</i>	<i>Amount expressed as per cent of GNP of donor nation</i>
The Netherlands	1 577	0.99
Norway	473	0.82
Sweden	923	0.76
Denmark	468	0.72
France	4 053	0.62
Belgium	581	0.49
West Germany	3 517	0.43
Canada	1 036	0.42
Great Britain	1 781	0.34
Japan	3 304	0.32
New Zealand	71	0.32
USA	7 138	0.27
Switzerland	246	0.24
Finland	106	0.22
Italy	672	0.17

Vast amounts (see Table 1) are provided as foreign aid. This aid is usually advantageous to developing countries, but in order to derive the greatest benefit, it should be in the form of investments that the country really needs. Some serious financial and sociological problems, as well as political scandals have arisen when developed, industrialised countries "help" the less-developed nations via financial grants and/or loans to developing nations (Ref. 80). Aid is not solely based upon the obvious humanitarian argument but also on enlightened self-interest, both in the short-term by protecting overseas investments and markets, and in the long-term by helping to expand such opportunities. Also quite understandably, aid is often tied to the procurement of goods and services from the donor nation. But the usefulness of many provided items of "western" plant and equipment to the non-industrialised rural population is arguably questionable and the result of this and other similar practices has

WIND-TURBINES FOR DEVELOPING COUNTRIES

Aid to less-developed countries

been the reinforcement of "dual societies" in most third world countries — a small powerful elite representing approximately 10 per cent of the population, living in considerable affluence, whereas the remainder of the population exist in the rural areas in abject poverty (Ref. 81).

Many developing countries (e.g. Bangladesh, Zambia and Sudan) are in considerable debt to the International Monetary Fund (IMF). This is partly due to the mandate of the IMF and also its relatively harsh conditions of granting loans. It was originally set up with the aim of providing short-term (i.e. 3 to 5 year) loans to "advanced" nations and generally insists on free-market policies, which may be at variance with the domestic needs of the developing country.

During the 1970's many developing countries experienced balance-of-payments difficulties and an increasing number of them began to seek assistance from the IMF in the form of long-term, rather than short-term loans. The IMF attempted to modify their role in order to accommodate these problems and fortify the economies of developing countries — by providing longer term loans thus alleviating balance-of-payments problems and attempting to foster greater stability — but this is becoming increasingly difficult because it does not fall within the IMF's existing mandate. Thus a change in the IMF's role, to place a greater emphasis on aid for the developing countries, could be of significant benefit to Third World nations.

Development aid has traditionally been in the form of finance for capital projects, but this help is more easily absorbed effectively by countries that have respected, stable economic and administrative structures. The donors have not always been able or willing to:-

1. able or willing to persuade governments of the poor countries to adopt effective policies with respect to applying the aid, or
2. to encourage the administrative institutions to utilise their local and available resources properly.

Unfortunately, aid is only rarely directed towards the most needy people: in 1979 middle income countries were receiving annual aid of US \$12 per head, whereas such aid amounted to only US \$2 per head for the poorest countries (Ref. 82).

The aid also tends to be discriminatory. For example the women's role in the Third World is being undermined by various aid programmes: they are losing their traditional role of working in the fields because, mainly it is men that are taught to use tractors and harvesters (Ref. 83). Therefore it is important that rural women as well as men are taught all the basic skills necessary to operate and maintain these "locally new" technologies.

The developing countries (containing as they do the majority of the world's population) and the developed countries are interdependent for trade. Hence the developed countries have a vested, long-term interest in helping Third World nations to prosper. During the

WIND-TURBINES FOR DEVELOPING COUNTRIES
Aid to less-developed countries

nineteen-seventies, the poorest countries were the most severely hurt by the deteriorating economic climate. Their terms of trade (i.e. the rate at which one country's products are exchanged for those of another) with the industrialised countries declined by 16 per cent, thereby greatly reducing their purchasing power in the world market. Although countries with oil reserves were still in a relatively strong position, this was not always so for developing countries with other types of mineral reserves (e.g. iron and copper): declining commodity prices in real terms caused further economic problems for them.

Despite the rate of overall food production in the developing countries keeping pace with population growth during the 1970's, by 1980, 750 million people (i.e. one third of the world's population, excluding China) were existing in absolute poverty. Millions of people are still starving and millions of children are suffering from malnutrition which will probably handicap them permanently. In spite of this, the developing nations' dependence upon food imports is increasing — due to the greater demand of the middle-income countries. This problem is becoming more acute as prices per tonne of grain imports rise, resulting in countries being forced to choose between food or oil imports — not an easy decision to make.

One partial solution to this problem is to concentrate development aid upon the agricultural sector. This is something that several small aid organisations have been trying to implement for many years. Belatedly, the World Bank has also realised that the development of agriculture encourages the growth of its economy in general (Ref. 84) and so considerable improvements in agriculture are anticipated in the near future.

Industrialisation of developing countries along "western" lines tends to result in even greater proportions of the populations subsisting below the poverty line, their highly evolved self-sustaining ways of life having been discarded, in one generation, by the introduction of inappropriate technologies. Third world governments believe that they are as entitled as the industrialised countries to exploit fossil fuels, nuclear power and technological advances. They dislike being relegated to depend upon the so-called "trendy" alternative energy sources (Ref. 85) but this attitude again often serves to widen the division between the élite and the rural poor, so failing to assist the vast majority of the population.

Politicians and civil servants also often exhibit a paternalistic attitude towards the rural poor: grant aid — for water wells, pumps and health services is usually decided by authorities remote from the villages and frequently with a lack of prior consultation with those whose needs are greatest. Prior discussions concerning the inhabitant's real needs are therefore required and instead of, for example, having an "outside" doctor to visit the village intermittently, a trained health worker (permanently residing within the village) could be employed more usefully and self-help schemes encouraged (Ref. 86). The same basic principle should apply to wind-turbines: with the help of grant aid and credit facilities they should be manufactured locally, in order to satisfy the needs of the villagers rather than be purchased from abroad.

WIND-TURBINES FOR DEVELOPING COUNTRIES IRRIGATION

4.3 IRRIGATION

Water is an essential need of any community, and often the rural poor spend many hours each day collecting sufficient quantities of it from distant wells. Rural electrification programmes have partially reduced this chore by enabling electric pump-sets to be used in conjunction with local bore holes, but many small villages are still without a (reliable) electricity supply because the costs of providing such facilities are prohibitively high. Rural electrification schemes have supplied villages preferentially within easy reach of major towns and cities, but the majority of outlying small villages (which house most of the rural population) are likely to remain without mains electricity for a considerable period (Ref. 72).

Table 2.
Typical present order of priority for energy use
in less-developed countries.

<u>Decreasing Urgency of Need</u> →			
	<i>1. Water raising in order to supply:</i>	<i>2. Shaft power (mechanical or electrical) for:</i>	<i>3. Other power applications, for example:</i>
Decreasing urgency of need ↓	(a) Humans	(a) Crop processing (e.g., drying and grinding)	(a) Small workshops and industries (e.g. saw-mills)
	(b) Crop irrigation	(b) Dairy purposes	(b) Community facilities

From Table 2, it is apparent that wind-turbines for water pumping possess great potential for use under these circumstances. As the majority of irrigation applications do not require stimulation at specific times each day, the wind-turbine is eminently capable of providing the necessary motive power.

4.4 HEATING AND LIGHTING

Traditional, flexible sail-type wind-turbines are widely used in many countries. They are slow running (having optimal tip-to-wind speed ratios of approximately unity) as well as having large solidities and high starting torques, so readily overcoming the relatively large torques required to start the majority of irrigation pumps. But whilst these wind-turbines are appropriate for water pumping, they are less suitable for providing heating and lighting, as high rotational speeds are generally needed for this purpose. Wood and dung are commonly used for heating and lighting in developing countries, but because wood is becoming increasingly scarce, villagers have to spend many hours per day collecting it and their sorties gradually lengthen. Also dung is a valuable soil conditioner — often too valuable to burn. Thus methods of reducing the population's dependence on wood and dung are increasingly being sought. Wind-electric and photo-voltaic solar systems are often suggested, despite their high conversion losses, inherent complexities and

WIND-TURBINES FOR DEVELOPING COUNTRIES

Heating and lighting

expense. Large-scale investments in such technologies should frequently be questioned in less-developed countries because they produce relatively low electric power outputs per US \$ expended: biogas generators would probably be far more effective. Small wind-electric systems are of greater benefit to the "more developed" regions.

4.5 RURAL ELECTRIFICATION

The rural populations of Third World countries generally rank rural electrification low on their list of priorities. Studies of the impact of electrification on the rural poor (Ref. 87) conclude invariably that the electricity users are the "better off" financially in any community. This rich/poor discrepancy is often exacerbated by the large aid organisations. They find it easier, administratively, to finance large capital programmes (such as centralised electricity supply systems) rather than a multiplicity of smaller ones that could be of far greater benefit to many more of the poor. In an attempt to generate profit from rural electrification schemes, the managements of the electricity-supply utilities must create a demand for their electricity, but as rural electricity is more costly than in urban conurbations, they have to promote consumption more aggressively than in the cities. This in turn leads to the use of electricity for a variety of grinding and other similar simple operations, so replacing the traditional use of manual labour. Thus rural electrification schemes can have the effect of creating even more unemployment and increasing the gap still further between the rural poor and the financially "better off".

Rural electrification also presents problems in the following areas:

1. a high degree of maintenance is necessary if frequent breakdowns in service are to be avoided,
2. large losses occur because of the long transmission lines, leading to low overall efficiencies for the central electricity network, and
3. poor load factors often ensue, leading to uneconomic operation.

These difficulties are inherent in connecting scattered, widely dispersed small villages to a central grid system. This has thus led to a growing interest in developing small-scale de-centralised energy conversion schemes that have minimal dependence upon imported fuel oils.

WIND-TURBINES FOR DEVELOPING COUNTRIES
SAIL-TYPE WIND-TURBINES AS A POWER SOURCE

4.6 SAIL-TYPE WIND-TURBINES AS A POWER SOURCE

Coventional (imported) wind-turbines with rigid vanes are widely used in developing countries. They have relatively high starting torques and so are suitable for water-pumping applications. However, improved designs for small wind-turbines can be built locally for around 50 to 150 US \$ per square metre of swept area — this is about half the cost of traditional imported models.

The capital needed could be still further reduced by using flexible fabric sails rather than wooden or metal blades. For the "Cretan" type of wind-turbine, each sail is held between 3 points, so forming a strong uniform surface with which to "catch" the wind. This provides a relatively simple, cheap method for harnessing wind power, with very little skill required for construction or maintenance. Hence the design has persisted in use for many hundreds of years.

Sail-type wind-turbines are lighter in weight than conventional multi-vane rotors and, after design adaption to suit a particular location and wind regime, can be manufactured in rudimentary equipped workshops. They can be cheaper than imported designs by a factor of two to four, thereby saving valuable foreign exchange.

However, proper matching of the wind-turbine and the pump is necessary to obtain efficient harnessing of the wind power. The median wind speeds of most developing countries are relatively low (i.e. 5 ms^{-1}), and so the designs of wind-turbines chosen should be such that they operate effectively at these speeds. Their pumping efficiencies in high speed winds are relatively unimportant because inefficiencies under these conditions can be tolerated; sufficient quantities of water would still be pumped with the higher velocity winds, even with their reduced pumping efficiencies.

Despite the self-regulating (and hence inherent rotational speed-governing) advantage of the sails, in very high winds, they would need to be furled to prevent overspeed and consequent damage to the wind-turbine. Also wind-driven water-pumps would not be required to operate throughout the year. The sails would be furled during the rainy season and partially furled during the pre-rainy season, when the wind-speeds are often relatively high. This furling would reduce the wear on various parts of the pump.

Table 2 also emphasises that a major use for energy in less-developed countries is for stimulating water-pumps (Ref. 88): the four commonest power sources for which are:

1. bullocks;
2. diesel engines;
3. electric motors; and
4. human labour.

WIND-TURBINES FOR DEVELOPING COUNTRIES

Sail-type wind-turbines

Draft animal power remains the most common and reliable irrigation power source for the rural poor in most developing countries. Wind-turbines of sizes that would permit pumping of similar quantities of water as can be achieved with bullocks, have an existing market, provided the wind-powered pumps can be acquired cheaply enough. Ensuring that wind-turbines have power take-off mechanisms to enable other processes to be undertaken, e.g. grain and sugar cane crushing, would significantly increase the usefulness of such wind-rotors and so make them even more competitive with the bullock. It is usually more efficient for wind energy to be harnessed directly at the irrigation site for pumping water, rather than partially converted into electricity to stimulate a water-pump. Electricity is expensive, because both the initial capital outlay is large and storage facilities are often necessary. Such facilities for water pumping wind-turbines are not required, as most crops can survive for periods of a few wind-less days, especially with rice cultivation, because there the field itself acts as the water store. However many problems have been encountered in attempting to implement such wind powered irrigation schemes. For instance:

1. expense; subsistence farmers are often unable to afford the relatively costly and usually imported, multi-vane type wind-turbines;
2. lack of credit facilities: schemes to assist farmers acquire wind-turbines do not exist, whereas such facilities are often available for diesel and electric pumps;
3. rural extension services; there are rarely services to help farmers install and maintain wind-turbines; and
4. awareness; there has been a lack of understanding of the potential of harnessing wind power in many developing countries.

Fortunately these problems are now becoming more widely recognised and the social environment for implementing wind-turbines is gradually improving.

Two other areas of concern, specific to wind-driven water pumps, are ownership and maintenance responsibilities. Clear explanations of a community's responsibilities for irrigation systems are required in order to ensure that they are properly looked after. As the cost of a wind-turbine is too high for the majority of third world farmers to afford one individually, community shared systems should be made more attractive. A number of small farms would then use a single wind-turbine as the irrigation power source for the whole community. Providing water sharing rationing schemes are agreed and responsibilities determined, the number of such systems is likely to increase.

4.7 POTENTIAL EXPLOITATION

In the past, small wind-driven water pumps have been used successfully in many rural areas of the world. They continue to operate to this day in regions where they were never superseded by low-cost electric and diesel pumps (Ref. 89). As there are many ($\sim 10^6$) such wind-driven pumps still in use around the world, it implies that the economically-viable potential market for them is very large — may be as high as one hundred million systems globally (Ref. 79). This market could be developed provided that the large development aid programmes become more appropriate to the needs of the rural poor populations, i.e. to help them develop truly indigenous industries.

Thus aid programmes to establish employment generating, rather than capital intensive industries, are required for many less-developed countries, as unemployment and under-employment are widespread. Consequently aid would be more profitably employed in establishing small village workshops. These could then manufacture low-technology consumer products and tools such as wind-turbines, so providing employment and reducing the energy problems for the indigenous rural population. They would also then become more self-sufficient with respect to food.

Increased self-sufficiency would avoid the direst effects of protectionism. Export-based economies, as many of the Third World countries are becoming, are always susceptible when protectionism is applied to their markets. In order to try to stabilize the economies of the developed countries, protectionism there increased during the 1970's. This was partly as a consequence of the militancy of the oil producing countries. It led to tragic economic problems for the Third World, and the World slump became even more severe.

All forms of economic co-operation should be fostered. For example, the revenue for the developing world arising from trade with Britain amounted to about twenty times (in 1980) that which they received in official aid from Britain. The developing countries could aim to produce a financially attractive and politically stable climate for foreign investment.

Multi-national corporations sometimes act in ways which are inimicable to the social and economic development of Third World countries. For example, some oil refineries in developing countries have been "run down" relative to those in the major share-holding countries during the economic recession of the last decade. This has naturally, but sometimes misguidedly resulted in the vociferous advocacy of nationalisation, in the developing country, as the complete answer to local economic problems, even though the world market for the locally produced commodity remains deflated.

WIND-TURBINES FOR DEVELOPING COUNTRIES
Potential exploitation

Another, highly relevant, form of aid is that of pertinent education (Ref. 90) The more affluent nations should be teaching the students of the developing world to help themselves via appropriate technologies rather than providing aid in the form of electric, or diesel pump-sets, subsidising their energy supply industries or providing tuition irrelevant to the immediate needs of the developing countries. Alas too often the Western world prescribes solutions prematurely to Third World problems, prior to them being properly identified and analysed.

CHAPTER 5

HORIZONTAL-AXIS WIND-TURBINES: CURRENT THEORETICAL UNDERSTANDING

The following theoretical analysis is based upon propeller-type horizontal-axis wind-turbines, which is itself derived from aircraft propeller theory.

The momentum consideration was first developed by Rankine (Ref. 91) in 1865 and further improved by Froude (Ref. 92). This is based upon determining the forces acting upon the rotor in order to produce the motion of the fluid. The theory proved useful in predicting the ideal efficiency and flow velocity of the wind-turbine, but gives no information about the blade or sail shape. Betz (Ref. 93) modified the analysis to include rotational effects of the wake.

Blade element theory was devised by Froude (Ref. 94) in 1878, with Drzwiecki (Ref. 95) later developing it further. This approach is inverse of that of momentum theory, in that it is concerned with the forces produced by the blades as a result of the fluid motion, rather than determining the forces on the blade to produce motion of the fluid.

Modern propeller theory developed from the concept of free vortices. These vortices are shed from the rotating blade and define the slipstream and generate induced velocities. Lanchester (Ref. 96) and Flamm (Ref. 97) developed the original concept whilst Joukowski (Ref. 98), Betz (Ref. 99), Prandtl (Ref. 100), Goldstein (Ref. 101) and Glauert (Ref. 102), further refined it.

The general analysis is given in section 5.3 onwards, whilst the first two sections (5.1 and 5.2) define the energy available in the wind and the various dimensionless coefficients used in the analysis.

5.1 THE ENERGY IN THE WIND

The kinetic energy per unit volume of air, flowing at velocity U , is given by, $\frac{1}{2}\rho U^2$.

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING Energy in the wind

If we consider air of volume flow-rate $\dot{V}$ passing through an area A , perpendicular to the wind direction (see Fig. 5) then the steady-state power developed is the product of kinetic energy flow per second, cross-sectional area of the stream tube and volumetric flow rate, i.e.

$$P_{air} = \frac{1}{2} \rho U^2 A \dot{V} \quad (1)$$

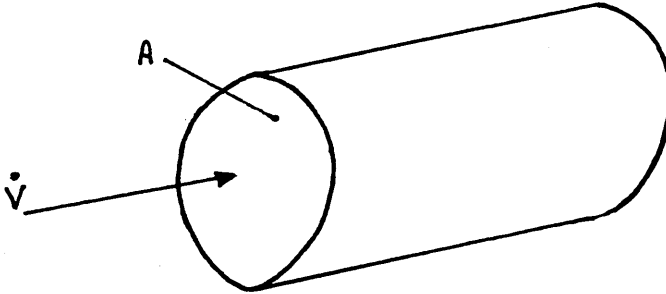


Fig. 5. Air of volume flow rate $\dot{V}$ flowing through disc of area A .

But for a horizontal-axis wind-turbine, $A = \pi R^2$ and $\dot{V} = UA$,

$$\therefore P_{air} = \frac{1}{2} \rho U^3 \pi R^2 \quad (2)$$

This is the steady-state power available from the wind.

5.2 WIND-TURBINE DIMENSIONLESS COEFFICIENTS

5.2.1 Lift And Drag Coefficients

All aerofoils require an angle of attack (α) to produce a lift force (L). This angle of attack is measured between the chord line and the direction of the air flow, where the chord line connects the leading and trailing edges of the aerofoil (see Fig. 6).

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING
Dimensionless coefficients

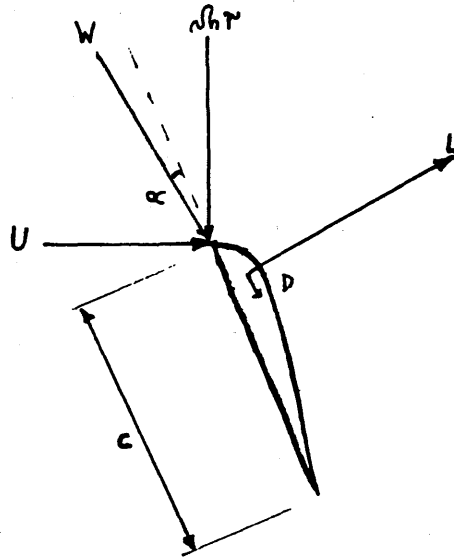


Fig. 6. Diagram showing angle of attack, chord line and forces acting on an aerofoil.

Non-dimensionalising the lift and drag forces gives;

$$C_L = \frac{L}{\frac{1}{2} \rho W^2 A} \quad (3)$$

$$C_D = \frac{D}{\frac{1}{2} \rho W^2 A} \quad (4)$$

Where C_L and C_D are the lift and drag coefficients respectively.

The angle of attack determines the amount of lift and drag that is produced and this relationship is a given characteristic of a rigid aerofoil.

For rigid propeller-type wind-turbine aerofoil section blades, the values of α , C_L , and C_D can be determined easily for given conditions using existing aerofoil characteristics. This facilitates the design of such rotors. However, these parameters are not so readily determined for a variable sail profile wind-turbine — i.e. the flexible sail wind-rotor. Thus the theoretical analysis presented in section 5.3 is not directly applicable to a flexible sail wind-turbine, although it can be used for a given (static) sail configuration. For maximum power harnessing by the wind-turbine, the ratio of the lift to drag forces should be as large as possible.

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING Dimensionless coefficients

5.2.2 Power Coefficient

The meaning of a term to describe the efficiency of a wind-turbine is arguable, because the energy harnessed from the wind by the wind-turbine is dependent almost only upon the size of the wind-turbine itself. Nevertheless an efficiency term is an important parameter as this facilitates comparison of the sizes, designs and costs of various rotors.

In the aerodynamic study of propellers, the efficiency is defined as $\frac{TV}{Q\Omega}$

where,

- T is the thrust in the direction of the axis of rotation,
- V is the forward speed in the direction of the axis of rotation,
- Q is the torque exerted by the engine, and,
- Ω is the angular speed of the shaft.

The conventional propeller theory suggests that the efficiency of a wind-turbine is the inverse of the that for a propeller, (taking the positive value if the propeller were operating as a brake), i.e.

$$\eta_{prop} = \frac{Q\Omega}{TV} \quad (5)$$

Such an efficiency term is relatively irrelevant to wind-turbines as it is not the aerodynamic efficiency, but rather the amount of energy harnessed from the wind, that determines its optimal operating conditions. Thus it is the power coefficient not the inverse of the aerodynamic efficiency that should be maximised for the optimal wind-turbine performance.

The power coefficient is the ratio of the power output of the wind-turbine to the power available in the wind of stream-tube area, A (i.e. the swept area of the wind-turbine), flowing at velocity U.

This enables us to compare the properties and characteristics of wind-turbines under different design conditions.

The mechanical power output is expressed as

$$P = C_p P_{air} \quad (6)$$

where C_p is the power coefficient and P_{air} is the power available in the wind,

$$C_p = \frac{P}{P_{air}} \quad (7)$$

From equation (2) the power available in the wind is $\frac{1}{2}\rho U^3 R^2 \pi$

$$\therefore C_p = \frac{P}{\frac{1}{2}\rho U^3 \pi R^2} \quad (8)$$

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING Dimensionless coefficients

5.2.3 Tip-to-wind Speed Ratio

The tip-to-wind speed ratio (λ) is the speed of the wind-turbine of radius, R , at its periphery, divided by the wind speed at the rotor.

$$\lambda = \frac{\omega R}{U} \quad (9)$$

5.2.4 Torque Coefficient

The torque coefficient is derived from the following equations

$$P = Q \omega \quad (10)$$

i.e. power is the product of torque and angular velocity.

$$C_p = \frac{P}{\frac{1}{2} \rho U^3 \pi R^2} \quad (8)$$

$$\text{and } \lambda = \frac{R \omega}{U} \quad (9)$$

From equations (8) and (9), we have:-

$$\frac{C_p}{\lambda} = \frac{P U}{\frac{1}{2} \rho U^3 R^2 \pi R \omega} \quad (11)$$

$$= \frac{P}{\omega} \left(\frac{1}{\frac{1}{2} \rho U^2 \pi R^3} \right) \quad (12)$$

But from equation (10), $Q = \frac{P}{\omega}$

Therefore,

$$\begin{aligned} \frac{C_p}{\lambda} &= \frac{Q}{\frac{1}{2} \rho U^2 \pi R^3} \\ &= C_q \end{aligned} \quad (13)$$

Where C_q is the torque coefficient.

Hence equation (10), can be expressed in dimensionless form as:-

$$C_p = C_q \lambda \quad (14)$$

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING
Dimensionless coefficients

5.2.5 Solidity Ratio

This is the ratio of the sail area to the area of the rotor swept by the sails, i.e.

$$\sigma = \frac{\text{Total sail area}}{\pi R^2} \quad (15)$$

or, alternatively, for sails or blades with a constant sail chord, c ,

$$\sigma = \frac{Bc}{2\pi R} \quad (16)$$

5.3 ANALYSIS OF WIND-TURBINE POWER CHARACTERISTICS

The wind-turbine's function is to transfer the linear kinetic energy of the air to rotational energy of the rotor. Inherent in this energy transfer are energy losses — e.g. frictional drag and the rotational motion of the turbine exhaust fluid. Thus as a first approximation of the wind-turbine's power characteristics, the following assumptions are made:-

1. the sails (or blades) operate without frictional drag;
2. the slip-stream is well defined and separates the flow through the rotor from the flow outside the rotor;
3. the static pressure far up-stream and far down-stream of the rotor are equal to the undisturbed free-stream static pressure;
4. no rotation of the wake is imparted by the rotor; and
5. the thrust loading is uniform over the rotor cross sectional area.

These assumptions are not entirely valid, but nevertheless they allow a preliminary theoretical analysis to be developed.

5.3.1 Maximum Power Available In The Wind

Using the above assumptions, the theoretical maximum power that can be harnessed by the unaugmented wind-turbine is derived as follows:-

If u_1 and u_2 are the wind speeds up-stream and down-stream of the wind-turbine respectively (see Fig. 7), then the rate of change of momentum per unit volume is:-

$$\dot{M} = \dot{m}(u_1 - u_2) \quad (17)$$

Where $\dot{m}$ is the mass flow rate of air.

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING Analysis of power characteristics

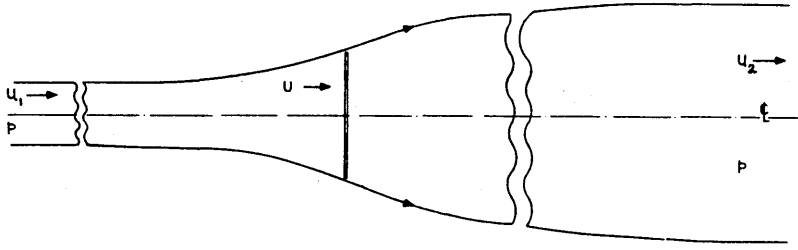


Fig. 7. Schematic representation of the flow through the wind-turbine.

The power is therefore:-

$$P = \dot{m}(u_1 - u_2)u \quad (18)$$

where u is the velocity of the air through the rotor.

The rate of change of kinetic energy (K.E.) is:-

$$\dot{K.E.} = \frac{1}{2} \dot{m}(u_1^2 - u_2^2) \quad (19)$$

Thus by continuity and assuming no losses,

$$\dot{K.E.} = P \quad (20)$$

Therefore,

$$\dot{m}(u_1 - u_2)u = \frac{1}{2} \dot{m}(u_1^2 - u_2^2) \quad (21)$$

and

$$u = \frac{u_1 + u_2}{2} \quad (22)$$

That is, the wind velocity through the rotor is the arithmetic mean of the velocity up-wind of the rotor and the wake velocity down-stream.

When a wind-turbine harnesses energy from the wind, a torque is generated. This torque creates tangential forces, so resulting in momentum changes in a tangential direction. Thus the factor, a , the axial interference factor is introduced.

This is defined as;

$$u = (1-a)u_1 \quad (23)$$

and using the definition of, a , and equation (22) gives

$$u_1(1-a) = \frac{u_1 + u_2}{2} \quad (24)$$

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING Analysis of power characteristics

then the velocity in the wake is,

$$u_2 = u_1 (1-2a) \quad (25)$$

Thus the wake induced velocity is twice that of the induced velocity in the plane of the rotor.

$$a = 1 - \left(\frac{u_1 + u_2}{2u_1} \right) \quad (26)$$

This implies that if the rotor absorbs all the energy, (i.e. $u_2 = 0$) then, a , would have a maximum value of $\frac{1}{2}$.

Because power is the product of mass flow rate and the change in kinetic energy, the power, P , is given by:-

$$\begin{aligned} P &= \dot{m} \Delta KE \\ &= \rho AU \left(\frac{u_2^2}{2} - \frac{u_1^2}{2} \right) \\ &= \frac{1}{2} \rho AU^3 4a(1-a)^2 \end{aligned} \quad (27)$$

or

$$P = 2\rho AU^3 a(1-a)^2 \quad (28)$$

The maximum power occurs when $\frac{dp}{da} = 0$,

Thus,

$$\frac{dp}{da} = 2\rho AU^3 (1-4a+3a^2) = 0 \quad (29)$$

giving,

$$a = 1 \text{ or } \frac{1}{3}$$

Maximum power thus occurs when $a = \frac{1}{3}$, so,

$$P_{max} = \frac{16}{27} \left(\frac{1}{2} \rho AU^3 \right)$$

Thus, with the given assumptions, the theoretical maximum power that can be harnessed by the unaugmented horizontal-axis wind-turbine is

$$P_{max} = 0.593 \left(\frac{1}{2} \rho U^3 \pi R^2 \right) \quad (30)$$

This gives a maximum power coefficient for an ideal wind-turbine of 0.593 and this value is often termed the Betz coefficient (Ref. 103).

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING
REDUCTIONS IN THE THEORETICAL MAXIMUM POWER OUTPUT

5.4 REDUCTIONS IN THE THEORETICAL MAXIMUM POWER OUTPUT

The basic assumption in the analysis presented above was that the flow through the rotor occurs in non-interacting circular stream-tubes.

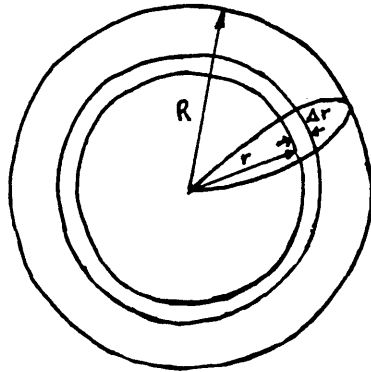


Fig. 8. Wind-turbine aerofoil blade annulus at radius r .

The flow at an element r (see Fig. 8) may thus be regarded as two dimensional. The established properties of aerofoil sections are then able to be used, as this information is strictly two-dimensional.

This assumption is not entirely valid, because the number of blades is always finite and the expression for maximum power output thus has to be amended to account for,

1. the presence of wake rotation,
2. the effect of lift and drag, and
3. tip losses.

These are discussed in the following sections.

5.4.1 Wake Rotation

The air has no tangential component of velocity before passing through the wind-turbine, but the velocity change (due to the presence of the rotor) causes a wake, down-stream of the rotor. This wake rotates in the opposite direction to that of the wind-turbine. That is, the flow up-stream of the rotor is assumed to be entirely axial and the flow down-stream to rotate with an angular velocity (ω), but remaining irrotational (see Fig. 9).

The rotation of the wake results in a loss of energy from the wind-turbine because the rotating air possesses kinetic energy that is not harnessed by the rotor. The power harnessed by the rotor is thus less, due to the rotation of the wake.

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING

Reductions in power output

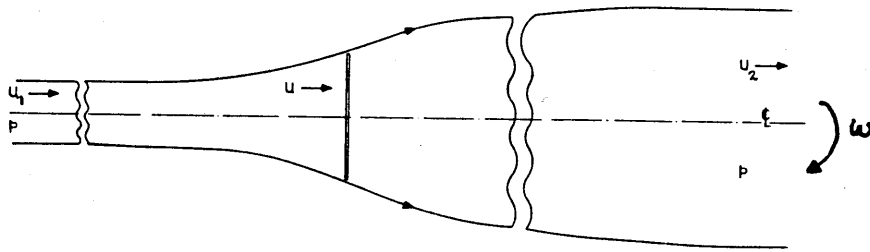


Fig. 9. Schematic representation of the flow through the wind-turbine with wake rotation.

$$\dot{KE} \text{ (up-wind)} = \text{Power extracted} + \dot{KE} \text{ (down-wind)} + \dot{KE} \text{ (rotational)}$$

This effect is more apparent in low tip-to-wind speed ratio wind-turbines, as they tend to generate higher torques, which in turn implies greater tangential velocities.

5.4.1.1 Derivation Of An Expression For Maximum Power Output Of A Wind-turbine -

The expressions for torque and power can be derived by considering the flow through an annulus at radius r , with area, ΔA .

$$\Delta A = 2\pi r \Delta R \quad (31)$$

Due to changing momentum in the air in a tangential direction, tangential forces act upon the rotor;

$$\begin{aligned} F &= \dot{m}(\Delta u) \\ &= \rho u \Delta A \omega r \\ &= 2\pi \rho u \omega r^2 \Delta r \end{aligned} \quad (32)$$

The torque generated in the annulus r (see Fig. 8) is :-

$$Q = 2\pi \rho u \omega r^3 \Delta r \quad (33)$$

But,

$$P = Q \omega \quad (10)$$

Thus

$$P = 2\pi \rho u \omega^2 r^3 \Delta r$$

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING Reductions in power output

So the developed torque on the wind-turbine becomes;

$$Q = 2\pi\rho \int_0^R u\omega r^3 dr \quad (34)$$

and the power harnessed

$$P = 2\pi\rho\lambda \int_0^R u\omega r^3 dr \quad (35)$$

To determine the maximum power, P_{max} , a relationship between u (the axial crossflow velocity through the wind-turbine) and ω (the angular velocity of the wake) is required.

This can be obtained by equating the axial force on an annulus at radius r , to the axial force on the same annulus, by considering the circulation at radius r .

Beurskens (Ref. 103) showed this relationship to be

$$u(U-u) = \frac{1}{2}\omega r \left(R + \frac{1}{2}\omega \right) r \quad (36)$$

Combining the above equation with the following

$$u = (1-a)U \quad (23)$$

$$\omega r = 2a' r \lambda \quad (37)$$

where a' is the tangential interference factor

$$\lambda_r = \frac{r\lambda}{U} \quad (38)$$

$$\lambda = \frac{R\lambda}{U} \quad (9)$$

$$C_p = \frac{P}{\frac{1}{2}\rho U^3 \pi R^2} \quad (8)$$

and

$$P = 2\pi\rho\lambda \int_0^R U\omega r^3 dr \quad (35)$$

gives,

$$C_p = \frac{8}{\lambda^2} \int_0^\lambda (1-a)a' \lambda_r^3 d\lambda_r \quad (39)$$

and

$$(1-a)a = a' (1+a')\lambda_r^2 \quad (40)$$

Wilson (Ref. 25) and Beurskens (Ref. 104) showed that the power integral of equation (39) can be made stationary subject to the constraint of equation (40).

This gives;

$$a' = \frac{(1-3a)}{(4a-1)} \quad (41)$$

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING Reductions in power output

This result, a relationship between a and a' , can then be used for the theoretical design of propeller-type wind-turbines, with blades of known aerofoil section.

Jansen (Ref. 105) varied values of a between the limits of $\frac{1}{4}$ and $\frac{1}{3}$, and produced an approximate expression for the power coefficient, C_p , accurate to within less than one per cent error, for tip-to-wind speed ratios greater than unity, namely:-

$$\frac{16}{17} e^{-0.3538\lambda - 1.2946\lambda^2}$$

This is shown graphically in Fig. 10

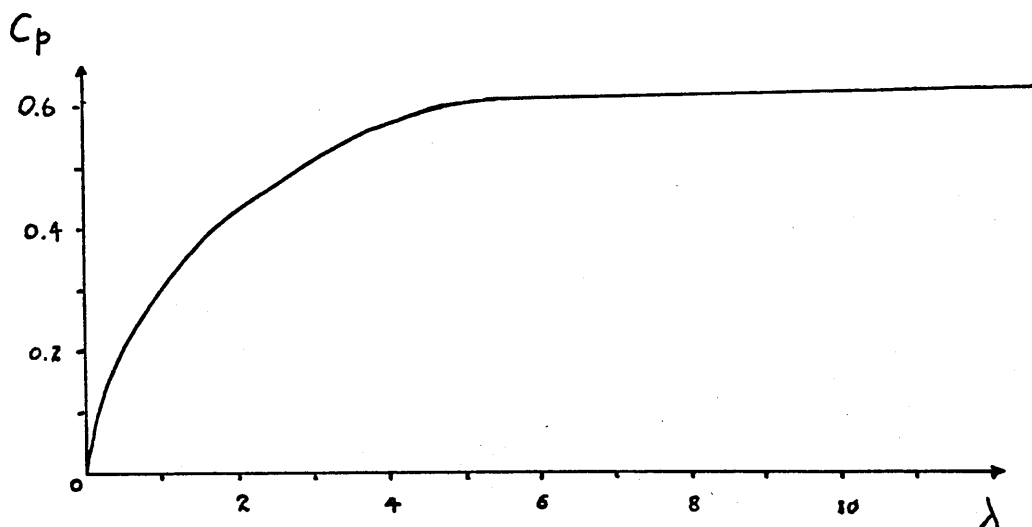


Fig. 10. Power coefficient as a function of tip-to-wind speed ratio for an ideal wind-turbine.

Fig. 10 may be interpreted as the characteristic of an ideal wind-turbine, with the assumptions that the flow is rotationally symmetric and frictionless.

In order that a wind-turbine should possess the characteristics of Fig. 10, the rotor must have an infinite number of blades and the blade angles and chords must vary limitlessly. Because this is not practical for horizontal-axis wind-turbines, it is more logical to interpret the above figure as a collection of power coefficient characteristics of different wind-turbines, operating at their own optimal tip-to-wind speed ratios.

Whilst these characteristics for ideal wind-turbines are useful in assisting the design of high speed rotors ($\lambda > 1$), they are not directly applicable to sail-type wind-turbines. These rotors generally have tip-to-wind speed ratios approximating to unity and thus Jansen's analysis is too inaccurate.

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING Reductions in power output

5.4.2 The Effect Of Lift And Drag

The drag coefficient C_D gives a measure of the flow resistance of the sails or blades to moving through the air. The ratio of the drag to lift coefficients C_D/C_L determines the power harnessing losses due to this resistance.

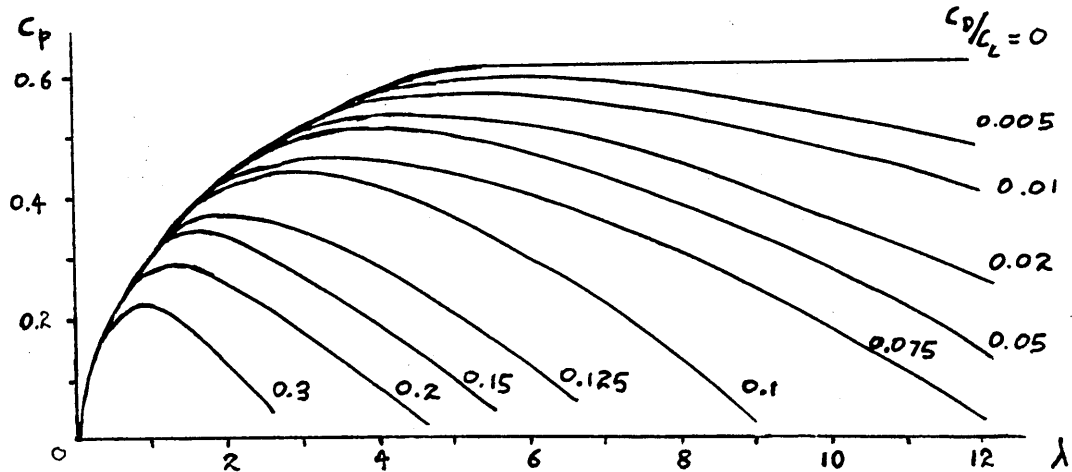


Fig. 11. The influence of the ratio of lift to drag coefficients on wind-turbine performance characteristics of an ideal wind-turbine, Ref. 105.

These losses are shown in Fig. 11 for a wind-turbine with an infinite number of blades.

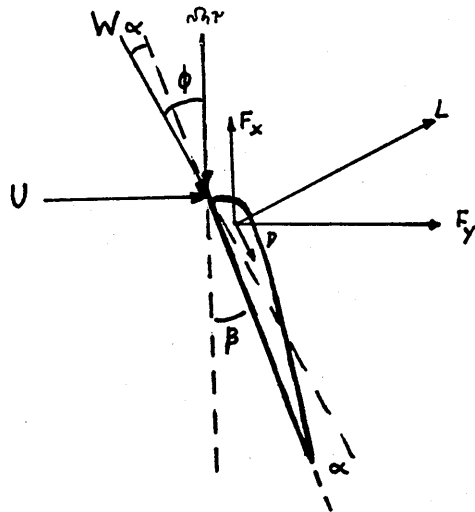


Fig. 12. Velocities and forces on a blade element at radius r .

An element at radius r from Fig. 8 is shown in Fig. 12. The rotational velocity is assumed to be half the value of the final velocity in the wake.

Defining the following relationships

$$C_D = \frac{D}{\frac{1}{2} \rho W^2 A} \quad (42)$$

$$C_L = \frac{L}{\frac{1}{2} \rho W^2 A} \quad (43)$$

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING

Reductions in power output

$$C_x = \frac{F_x}{\frac{1}{2} \rho W A} \quad (44)$$

$$C_y = \frac{F_y}{\frac{1}{2} \rho W A} \quad (45)$$

and as $A = c\Delta r$, where c is the length of the blade chord, the following trigonometrical relations can be obtained;

$$\alpha = \phi - \beta \quad (46)$$

$$\tan \phi = \frac{1-a}{1+a} \frac{u}{r\Omega} \quad (47)$$

$$C_y = C_L \cos \phi + C_D \sin \phi \quad (48)$$

$$C_x = C_L \sin \phi - C_D \cos \phi \quad (49)$$

Expressions may now be deduced for the thrust, T , and torque, Q , on the element Δr at radius r ;

$$dT = Bc \frac{1}{2} \rho W^2 C_y dr \quad (50)$$

$$dQ = Bc \frac{1}{2} \rho W^2 C_x r dr \quad (51)$$

From the previous analysis (see section 5.3.1 — equation (21) and section 5.3.2.1 — equation (33)), we can derive

$$dT = (2\pi r dr) u_i (U - u_i) \quad (52)$$

$$dQ = (2\pi r dr) U \omega r \quad (53)$$

Equations (52) and (53) were obtained from momentum theory. This theory does not include effects due to friction. So we may only equate the thrust and torque of equations (52) and (53) to (50) and (51) if we assume the drag coefficient C_D is equal to zero.

Using (23) and (36), the following equations can be derived

$$\frac{a}{1-a} = \frac{\sigma C_L \cos \phi}{4 \sin^2 \phi} \quad (54)$$

$$\frac{a'}{1+a'} = \frac{\sigma C_L}{4 \cos \phi} \quad (55)$$

where

$$\sigma = \frac{Bc}{2\pi R} \quad (16)$$

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING

Reductions in power output

Combining these equations with equations (47), (54) and (55) leads to equation (35) in dimensionless form. An iterative method for calculating the flow conditions at an element Δr at radius r is given in Ref. 25. This enables the sectional flow properties of the aerofoil blades to be determined and hence the overall torque and thrust on the rotor.

5.4.3 Tip Losses

The analysis presented in previous sections assumes that the flow through the rotor is rotationally symmetric. With a finite number of blades this assumption is not valid. Radial acceleration and wake induced flow at the tips alter the assumed flow pattern. Wilson (Ref. 25) suggested that, for most wind-turbines, the radial acceleration term can be neglected, but the effects result in performance losses concentrated near the periphery of the rotor — i.e. tip losses.

A horizontal-axis wind-turbine is essentially a lift producing aerofoil and can be represented by a distribution of bound vortex filaments which give rise to a circulation around the blade (analogous to finite wing theory). These vortex filaments from the trailing edge of the blade then "roll up" together to form a single helical trailing vortex behind the tip of each blade.

The wake rotation is caused by the trailing vortex sheets being shed from the blade into the wake. It is of the form of a multi-start helix and the induced flow causes an effective drop in circulation around the blade. This is particularly noticeable for the hub and tip regions of the wind-turbine.

Tip losses (i.e. reductions in the circulation of the air near the tip and the hub of the rotor) occur due to the interaction of the shed vorticity with the air flow near the rotor tips. These losses have been theoretically analysed (Refs. 25, 100, 101, and 105) and the detail and complexity of the solutions vary considerably.

Tip losses are further discussed in Chapter 8, section 8.2.2 and Chapter 12, section 12.3.2.

5.5 CASCADE THEORY

With high solidity wind-turbines it is necessary to account for the flow blockage of the air as it passes through the rotor blades. Considering the wind-turbine as a cascade of aerofoils and following the assumptions of McCormick (Ref. 25) it can be shown that the sectional angle of attack of the blades is reduced due to this relatively high solidity.

HORIZONTAL-AXIS THEORETICAL UNDERSTANDING
CURRENT UNDERSTANDING

5.6 CURRENT UNDERSTANDING

The preceding theoretical understanding was derived specifically for rigid sail profile, propeller-type wind-turbines. It assumed in particular that the wind-turbine had rigid, non-varying sail (or blade) profiles and high (i.e. greater than unity) tip-to-wind speed ratios. These two assumptions do not apply to sail-type wind-turbines and so the analysis is not strictly relevant to them. Nevertheless, provided that the profile of the sail is known, and neglecting the error in the tip-to-wind speed ratio, it is possible to obtain a mathematical expression to describe the performance of sail-type wind-turbines.

As the sail profile is not constant (it is dependent upon wind speed and direction), and we cannot use the NACA aeronautical data to describe the sail profile, an expression is required to outline the sail profile under known conditions. An expression for such a sail is presented in Chapter 7.

Once this sail profile is known, then the conventional theory can be applied to describe the behaviour of the wind-turbine for one particular wind speed. Although all the assumptions made in the analysis would not be strictly applicable, it can provide a basic theoretical understanding of the performance of the horizontal-axis sail-type wind-turbine.

CHAPTER 6

VERTICAL-AXIS WIND-TURBINES: CURRENT THEORETICAL UNDERSTANDING

The operation of the Savonius rotor is similar to any other wind energy conversion device. The air-flow produces an aerodynamic force on the sail (or blade) and this sail moves with a component of the aerodynamic force in the direction of motion. Thus work is done on the rotor and energy extracted from the air-flow. Despite this similarity, the theoretical analysis of the Savonius-type wind-turbine differs significantly from that of horizontal-axis rotors.

The sails are alternatively rotating "with" and "against" the wind during each rotation of the rotor, so complicating the analysis. In spite of this difference, it is inevitable that comparisons of performance characteristics will need to be made with horizontal and vertical-axis wind-turbines. Thus the vertical-axis wind-turbine theoretical analysis has many similarities to that of the horizontal-axis.

6.1 ENERGY IN THE WIND

A simplified expression for the steady-state power in the wind available for a horizontal-axis wind-turbine to harness is;

$$P_{air} = \frac{1}{2} \rho U^3 \pi R^2 \quad (2)$$

See Chapter 5, section 5.1

For a vertical-axis wind-turbine,

$$P_{air} = \frac{1}{2} \rho U^3 A_s \quad (56)$$

where A_s is the area swept by the rotor. If $A = zd$, where d is the "diameter" of the Savonius wind-turbine and z is the length of the rotor, as shown in Fig. 13, then,

$$P_{air} = \frac{1}{2} \rho z d U^3 \quad (57)$$

VERTICAL-AXIS THEORETICAL
GENERAL THEORETICAL ANALYSIS

6.2 GENERAL THEORETICAL ANALYSIS

The basic aerodynamic interpretation of the operation of a Savonius wind-turbine is that the vane section which is momentarily concave to the wind (i.e. the momentum capture phase of operation) has a high drag force acting on it. Thus this causes the device to rotate. It is also suggested (Ref. 71), that at low vane angles of attack, the vanes are subject to lift forces and that these forces also contribute to the power harnessed.

Wilson (Ref. 25) attempted to formulate a theory to describe the behaviour of the rigid-vaned Savonius-type wind-turbine. However, this analysis is in its infancy and incomplete in that it only considers the "S" rotor (i.e. the two-vaned Savonius rotor without a central gap). It is thus not readily applicable to the variable sail profile Savonius wind-turbine, although if the shape of all the sails could be expressed mathematically at a particular instant of time, then (using the two-dimensional sail equation in Chapter 7, section 7.4), Wilson's preliminary theoretical description would apply. This would only refer to one particular sail geometry, at one particular instant of time and so would be limited in its usefulness.

Thus whilst the theoretical analysis of horizontal-axis wind-turbines is well established (see Chapter 5), the analysis for rigid-vaned Savonius wind-turbines is far from complete, and that for sail-type Savonius rotors, virtually non-existent.

6.3 DIMENSIONAL ANALYSIS OF THE SAVONIUS PANEMONE

A dimensional analysis technique was employed in order to determine the basic relationship between the various parameters of the Savonius wind-turbine.

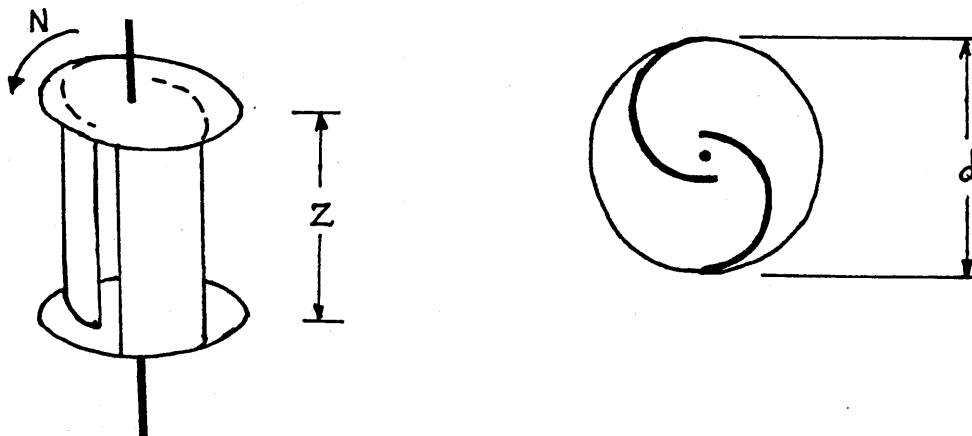


Fig. 13. Nomenclature of the Savonius wind-turbine.

VERTICAL-AXIS THEORETICAL
Dimensional analysis

Possible independent parameters (and their dimensions) affecting the output torque Q , of a Savonius wind-turbine for a given geometrical shape are;

Independent Parameter	Basic Units
ρ density of the fluid	ML^{-3}
μ dynamic viscosity of the fluid	$ML^{-1}T^{-1}$
u speed of the fluid	LT^{-1}
d diameter of the rotor	L
N rotor's rotational speed	T^{-1}
β compressibility of the fluid	$ML^{-1}T^{-2}$
a velocity of sound	LT^{-1}
z rotor length	L

One set of possible dimensionless groups is:-

$$\phi \left(\frac{U d \rho}{\mu}, \frac{Q}{\rho U d^3}, \frac{N d \pi}{U}, \frac{\beta}{\rho U^2}, \frac{U}{a}, \frac{P}{\frac{1}{2} \rho z d U^3} \right) = 0 \quad (58)$$

For incompressible flow and low speed fluids, these reduce to;

$$\phi \left(\frac{U d \rho}{\mu}, \frac{N d \pi}{U}, \frac{Q}{\rho U^2 d^3}, \frac{P}{\frac{1}{2} \rho U^3 z d} \right) = 0 \quad (59)$$

All the dimensionless groups cannot be satisfied simultaneously if the rotor size or wind velocity are to vary. But if the flow near or in the rotor is turbulent, viscous forces are likely to be negligible compared with inertial forces. Therefore the Reynolds number term can be neglected.

This gives;

$$\phi \left(\frac{N d \pi}{U}, \frac{Q}{\rho U^2 d^3}, \frac{P}{\frac{1}{2} \rho z d U^3} \right) = 0 \quad (60)$$

The performance may then be expressed in terms of the remaining groups;

$$C_Q = \frac{Q}{\rho U^2 d^3} = \phi \left(\frac{\pi N d}{U} \right) \quad (61)$$

$$C_P = \frac{P}{\frac{1}{2} \rho U^3 z d} = \phi \left(\frac{\pi N d}{U} \right) \quad (62)$$

VERTICAL-AXIS THEORETICAL Dimensional analysis

The tip-to-wind speed ratio of a Savonius rotor can be expressed as $\frac{11Nd}{U}$. Thus,

$$C_Q = f(\lambda) \quad (63)$$

and

$$C_P = f(\lambda) \quad (64)$$

This is analogous to the theoretical analysis for horizontal-axis wind-turbines, i.e. the power and torque coefficients are both proportional to the tip-to-wind speed ratio. But where the power coefficients for horizontal-axis wind-turbines are proportional to the rotor disc area, those for the Savonius types of rotor are not. Savonius-type vertical-axis wind-turbine power and torque coefficients are proportional to the "working sail" area — i.e. that part of the sail in the "momentum capture" phase of operation.

6.4 POWER COEFFICIENT

The power coefficients for vertical-axis wind-turbines are not identical to those for horizontal-axis rotors and that for the vertical-axis wind-turbine is not readily determined via the same procedure. Nevertheless, as the power coefficient is a convenient way of expressing the performance of a wind-turbine, it is advantageous to derive equations for the power coefficient of the vertical-axis wind-turbine.

We need to determine the power delivered, by the wind, of density, ρ , to a moving surface of area, A_s . The force on such a surface is $C_f \frac{1}{2} \rho A_s (U - u_s)^2$ where C_f is a coefficient of pressure (that varies with the form, nature and size of the surface) and u_s is the velocity of the surface as it moves in the direction of the wind. The relative velocity is thus $(U - u_s)$.

The power harnessed from the wind by such a system is,

$$P = A_s (U - u_s)^2 u_s \quad (65)$$

if $\gamma = \frac{u_s}{U}$ then,

$$P = C_f \frac{1}{2} \rho A_s U^3 (1 - \gamma)^2 \gamma \quad (66)$$

Differentiating with respect to γ and equating to zero, we obtain,

$$(\gamma - 1)(3\gamma - 1) = 0 \quad (67)$$

Thus $P_{\max}$ occurs when $\gamma = \frac{1}{3}$

VERTICAL-AXIS THEORETICAL Power coefficient

Substituting this in the power equation — equation (66) — gives,

$$P_{\max} = \frac{4C_f}{27} \rho A_s U^3 \quad (68)$$

Thus the maximum power coefficient is,

$$C_{P_{\max}} = \frac{4C_f}{27} \quad (69)$$

This is different from that for a horizontal-axis wind-turbine (see Chapter 5, section 5.2.2), as the two halves of the rotor move both with and against, the wind, during each revolution of the wind-turbine. The maximum power coefficient is proportional to the parameter C_f , where C_f is dependent upon the pressure distribution on the Savonius sail (or vane). As the Savonius wind-turbine derives its rotational thrust primarily from drag forces, C_f may be approximated to C_D , the drag coefficient experienced by the wind-turbine. Taking the drag coefficient to be 1.42 (i.e. C_D for a hollow hemisphere) gives a maximum power coefficient of 0.21, based upon the "momentum capture" phase of rotor operation.

This value takes no account of lift forces, nor of the Magnus effect, contributing to the power harnessing capabilities. It should thus only be regarded as a conservative first approximation to the theoretical maximum power coefficient of the Savonius wind-turbine.

6.4.1 Reductions In The Theoretical Maximum Power Outputs

As with the horizontal-axis wind-turbine theoretical analyses, the assumptions made in the preceding section are not entirely valid for the "real" wind-turbine. Energy losses occur, and the major sources of these losses are discussed in the following two sections (i.e. sections 6.4.1.1 and 6.4.1.2).

6.4.1.1 End Losses -

Frictional effects on cylinders rotating in an air stream produce circulations similar to those around an aerofoil. The direction of the force (i.e. the Magnus effect) is always in the direction away from the side where the circulation and the flow oppose each other — see section 6.5. Adding projecting fins (i.e. end-plates) to the ends of the Savonius (and also Flettner) rotors reduces the amount of disturbance caused by the circulations. As otherwise the air at the end of the cylinder, which is not rotating with the cylinder, is forced into the low pressure region at the suction side, where it tends to disturb the flow, so reducing the rotor's rotational speed.

VERTICAL-AXIS THEORETICAL
Power coefficient

6.4.1.2 Side Losses -

The Savonius wind-turbine, when rotating, engorges air from a smaller cross-sectional area than that of the rotor itself (see Fig. 14).

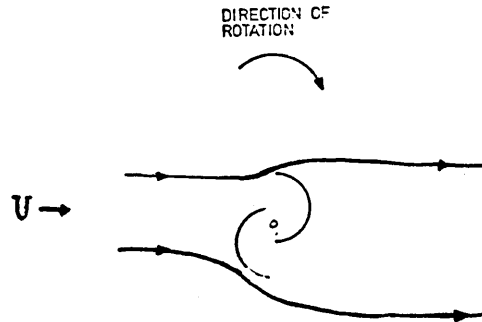


Fig. 14 Schematic representation of the flow through a 2-vaned Savonius wind-turbine

Thus taking the value of A_s , the rotor swept area to be $z d$ (see Fig. 13), gives an under-estimate of the rotor's power harnessing capabilities as the actual wind capture area is less than $z d$. Similarly using deflectors (see Fig. 15) on the Savonius rotor can increase the capture area of the wind and so enhance the wind-turbine's power output.

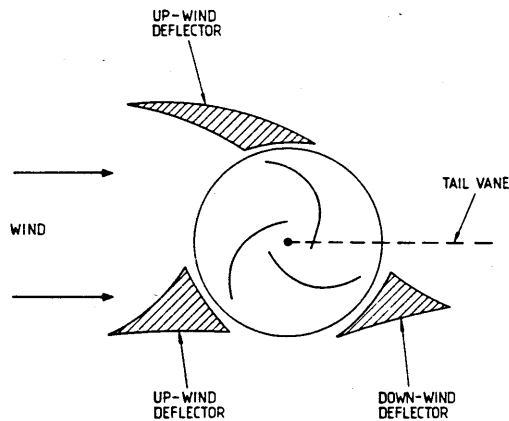


Fig. 15. Wind deflectors for a sail-type Savonius wind-turbine. The deflectors are rigidly connected and rotate about the common axis. By means of a tail-vane, they would always be aligned with the wind.

Various concentrators have been investigated for employment with rigid, two-vaned Savonius wind-turbines, (Refs. 17, 18 and 19) and substantial power enhancements are said to be possible. But whether the additional power harnessed from the wind can be economically justified by the extra capital cost of the wind-turbine, is arguable.

VERTICAL-AXIS THEORETICAL
THE DIRECTION OF THE MAGNUS FORCE

6.5 THE DIRECTION OF THE MAGNUS FORCE

The Savonius wind-turbine was derived from the Flettner rotor (Ref. 39), but whilst Flettner's rotors relied entirely upon the Magnus force (Ref. 60) for propulsion, the Savonius (Ref.13) "split" Flettner rotors do not. The exact extent to which Savonius rotors generate thrust via the the Magnus force is difficult to assess but it is useful to determine in which direction the lift force operates by considering an irrotational vortex in a potential flow over a cylinder.

From two-dimensional flow, the stream function ψ is defined as ;

$$\begin{aligned} \frac{\partial \psi}{\partial y} &= u & \frac{\partial \psi}{\partial x} &= -v \\ \frac{1}{r} \frac{\partial \psi}{\partial \theta} &= v_r & -\frac{\partial \psi}{\partial r} &= v_t \end{aligned}$$

and the velocity in the x-y plane is shown in Fig. 16.

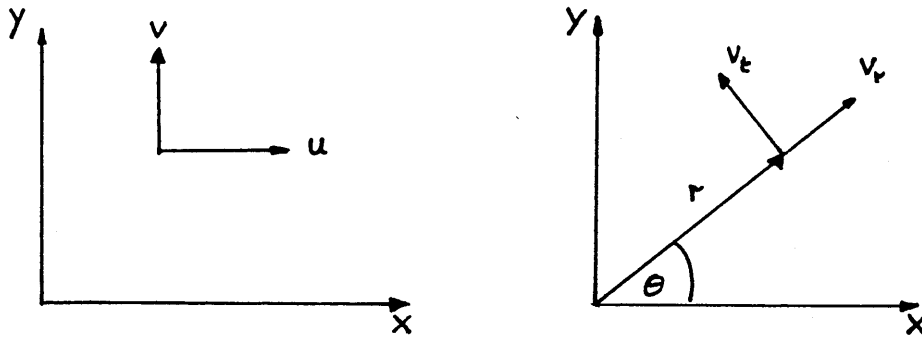


Fig. 16. Velocity nomenclature in the x-y plane

Consider the potential flow of an ideal (inviscid and incompressible) fluid over a cylinder of radius a , where the velocity is uniform in the x-direction at large distances from the cylinder.

The stream function for this flow is $U \sin \theta (r - \frac{a^2}{r})$ where $\psi = 0$ at the cylinder boundary.

The stream function for the irrotational vortex of circulation Γ , where;

$$\Gamma = v_t r 2\pi \quad (70)$$

is given by, $-\frac{\Gamma}{2\pi} \log_e \frac{r}{a}$

Superimposing the irrotational vortex on the flow over the cylinder, gives;

$$\psi = U \sin \theta (r - \frac{a^2}{r}) - \frac{\Gamma}{2\pi} \log_e \frac{r}{a} \quad (71)$$

VERTICAL-AXIS THEORETICAL
Direction of the Magnus force

This gives

$$v_t = -U \sin \theta \left(1 + \frac{a^2}{r^2} \right) + \frac{T}{2\pi r} \quad (72)$$

On the surface of the cylinder, $v_r = 0$,

$$v_t = \frac{T}{2\pi a} - 2U \sin \theta \quad (73)$$

Applying Bernoulli's equation to the flow gives the pressure at the boundary of the cylinder, p_b , (see Fig. 17), in terms of the static pressure at a point remote from the cylinder p_o .

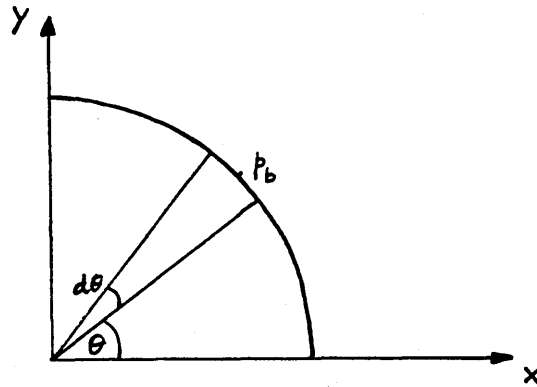


Fig. 17. Pressure p_b at a point on the boundary of a cylinder.

$$p_b + \frac{1}{2} \rho v_t^2 = p_o + \frac{1}{2} \rho U_o^2 \quad (74)$$

$$p_b = p_o + \frac{1}{2} \rho (U^2 - v_t^2) \quad (75)$$

The Magnus force, F , in the Y-direction is thus given by,

$$F_m = - \int_{-\pi/2}^{\pi/2} p_b z d \sin \theta d\theta \quad (76)$$

$$F_m = -z d \int_{-\pi/2}^{\pi/2} p_b \sin \theta d\theta \quad (77)$$

Substituting for v_t and p_b from equations (73) and (75) and evaluating the definite interval gives,

$$F_m = -T \rho U z \quad (78)$$

That is, the force is negative in the negative y-direction for both U and T , see Fig. 18.

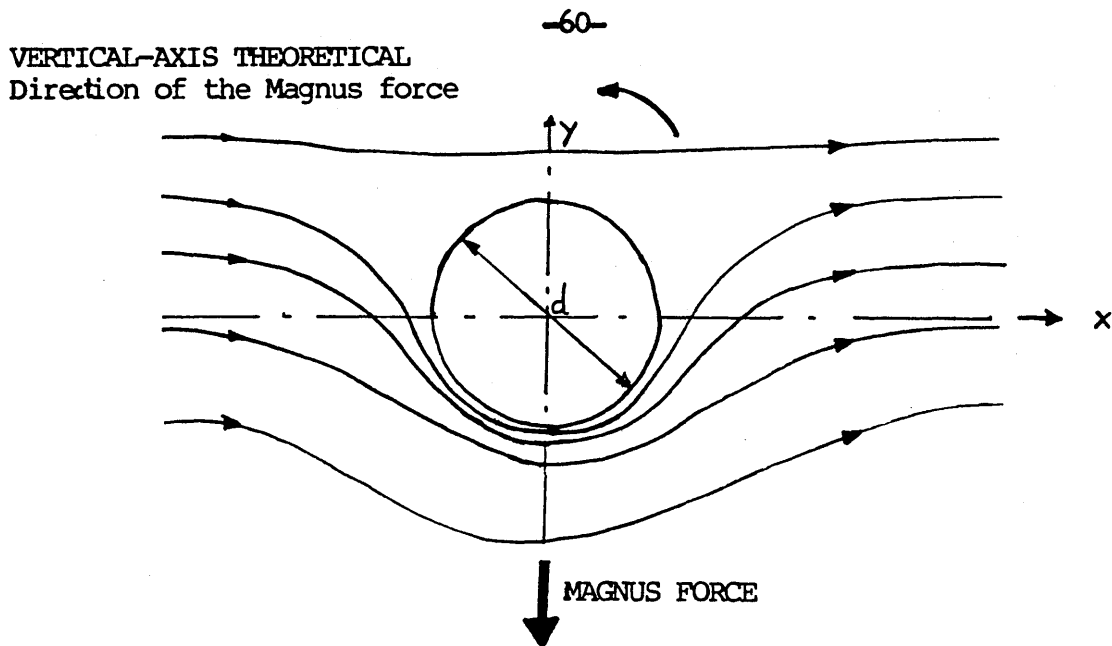


Fig. 18. Direction of the Magnus force on a rotating cylinder, in a uniform wind stream.

6.6 CURRENT THEORETICAL UNDERSTANDING

From the preceding sections, it is apparent that the theoretical analysis of the Savonius-type vertical-axis wind-turbine is in its infancy. Whilst our understanding is essentially based upon the aeronautical research of the past century (see Chapter 5), this knowledge cannot be utilised to as great an extent as that for the horizontal-axis wind-turbine. Thus our theoretical understanding of the Savonius wind-turbine is more difficult to describe mathematically. Although the behaviour of the rigid 2-vaned Savonius "S" rotor (without end-plates) has been seriously investigated (Ref. 25), that for the flexible-sail rotor — and also for rotors with a central gap or end-plates, — has not.

The theoretical analysis of the behaviour of yacht sails (see Chapter 7), can provide a mathematical description of the sail shape and the pressure distribution on that sail, in a uniform wind. But such an expression is unable to describe an operating (i.e. rotating) Savonius wind-turbine, because it assumes a uniform relative wind speed. As the Savonius wind-turbine sails rotate about the vertical-axis, the relative wind speed of the air to the sail is continually changing, so complicating the mathematical analysis.

CHAPTER 7

SAIL-TYPE WIND-TURBINES: A REVIEW OF PERTINENT THEORETICAL ANALYSES

Our theoretical understanding of the mode of operation of propeller-type wind-turbines is now well established, whereas even preliminary theoretical analyses of the behaviours of flexible-sail type wind-turbines are virtually non-existent. This Chapter presents a preliminary stage in the process of rectifying this omission. Previous theoretical investigations about the pertinent aerodynamics of yacht sails are reviewed and their possible modifications to describe the behaviours of flexible-sail wind-turbines discussed.

7.1 INTRODUCTION

The theoretical analyses of the behaviours of aerodynamic surfaces have been concerned almost exclusively with rigid or almost rigid systems; little pertinent research being undertaken with respect to flexible surfaces. The major reason for this omission is that the shape of a flexible sail and the pressure difference to which it is subjected cannot be specified in advance, because they are interdependent. With a rigid surface, the shape is fixed and thus only the pressure difference is needed in order to obtain a solution. Also there is no comprehensive library of aerodynamic information for wind-turbine flexible sails currently available, whereas the performance characteristics for propeller-type wind-turbines have been measured experimentally and are comprehensively documented (see e.g. NACA aeronautical data).

It is apparent that the conventional horizontal-axis rigid wind-turbine theory (see Chapter 5) is not readily applicable to flexible-sail wind-turbines. So this Chapter is regarded as a preliminary step towards the development of an aerodynamic theory for describing the behaviour of wind-turbine flexible sails.

7.2 AERODYNAMICS OF YACHT SAILS

Although the theoretical study of flexible-sail wind-turbines is still in its infancy, considerable research effort has already been devoted to improving our understanding of the aerodynamics of yacht sails. The first detailed investigation was undertaken by Voelz (Ref. 106) in the 1950's, although Cisotti (Ref. 107) modelled a

FLEXIBLE-SAIL THEORETICAL
Yacht sail aerodynamics

simple sail in the 1930's. However the major breakthrough came in the 1960's when Thwaites (Ref. 108) and Nielsen (Ref. 109), via different analyses, came essentially to the same conclusion. Their research concentrated on two aspects of yacht sails:-

1. two-dimensional linearised flow theory applied to flexible sails; and
2. three-dimensional lifting-line and lifting-surface theories applied to rigid sails.

As the three-dimensional theories apply only for rigid sails, we consider here the present status of two-dimensional theories for flexible-sails.

The behaviours of flexible sails are complicated to describe exactly because each sail's shape will vary with the wind load imposed upon it. Thus there are two basic inter-related problems:-

1. to predict the sail shape at a particular time for a given wind loading; and then,
2. to determine the lift experienced by that shape of sail and hence the torque exerted upon the rotor at that instant of time.

7.2.1 The Sail

For the two-dimensional theoretical abstraction, the sail is considered to be an infinitesimally thin, inextensible, perfectly flexible, aerofoil — possibly porous, with the leading and trailing edges held rigidly a fixed distance, c , apart (see Fig. 19).

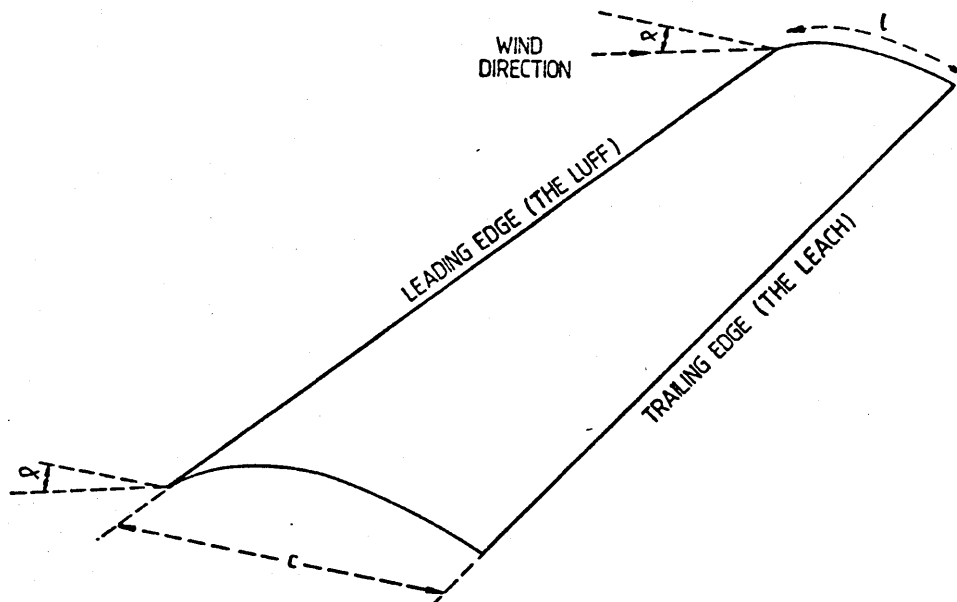


Fig. 19. Nomenclature for a two-dimensional sail at an angle of incidence α to the wind.

FLEXIBLE-SAIL THEORETICAL
Yacht sail aerodynamics

The sail is attached to these two parallel infinitely-long rigid masts, which are assumed to be so thin as to not affect the air flow appreciably. Thus there is a slack of $l-c$ in the sail.

If a uniform wind blows onto the sails, at an angle of attack, α , to the plane of the two masts, it causes the sail to fill and so become taut. It thus takes up a shape determined by the wind's magnitude and direction, as well as by the flexibility of the material used.

7.2.2 Previous Research On Two-dimensional Flexible Yacht Sails

During the 1920's, Warner and Ober (Ref. 110) carried out experimental tests on a full-sized yacht. They observed the air flows and pressure distribution over the sail, and the interference to the air flows produced by the mast and jib. Measurements were taken under a variety of sailing conditions and so the data obtained could not be compared meaningfully with each other due to variations in the sail's angle of attack to the wind.

In the 1930's, Cisotti (Ref. 107), produced a mathematical model describing the air flows over a two-dimensional non-porous sail. This was a free stream-tube model, in which the flow separated at the trailing edge of the sail, thereby forming a quiescent wake. Although Cisotti did not publish the data predicted from his two-dimensional model, Dugan (Ref. 111) subsequently used this model for his studies in the 1970's.

In the Voelz model (Ref. 106), with the exception of the boundary conditions, the sail was replaced by a linear distribution of vortices (as in thin aerofoil theory). He chose the sail shape and obtained a first eigenvalue solution of the linear integral equation of the strength of the vortex sheet. However it was Bugler (Ref. 112) who undertook the first major theoretical analysis using the assumptions of thin aerofoil theory. His findings broadly agreed with those of Thwaites (Ref. 108) and Nielsen (Ref. 109).

The research by Thwaites during the 1960's repeated, to some extent, that of Voelz, but also showed the existence of higher eigenvalues. He used linearised thin aerofoil theory to relate the sail shape to the loading imposed upon it. Thwaites obtained an integral-differential equation (i.e. the sail equation), which he converted into matrix form at a number of chord-wise points, and then solved numerically.

Also during the 1960's, Nielsen (Ref. 109), carried out theoretical and experimental investigations into the two-dimensional aerodynamic characteristics of flexible, infinitesimally-thin, aerofoils. He formulated the theoretical problem in terms of differential equations for the camber and aerodynamic loading of the sail. (These were based upon Fourier series and numerical matrix techniques, rather than integral equations as used by Thwaites). He concluded that the behaviour of a flexible sail is strongly dependent upon the tension it experiences.

FLEXIBLE-SAIL THEORETICAL Yacht sail aerodynamics

Later in the 1960's, Chambers (Ref. 113), demonstrated that variational methods could be applied to solve the Thwaites "sail equation". Barakat (Ref. 114), studied the influence of the porosity of the sail, based upon the Thwaites' analysis. For a non-porous sail, this equation is of singular integral form of the second kind. Barakat also extended the theory to a two-lobed sail.

During the late 1960's, Chapleo (Ref. 115) reviewed the published two-dimensional sail research. He stated that existing (i.e. pre-1968) theories led to over-estimates of the lift due to camber and, less seriously, to under-estimates of the lift due to wind incidence.

Dugan (Ref. 111), used the behavioural model that was first developed by Cisotti (Ref. 107) in the 1930's. He solved the equations numerically in order to obtain profiles of the sail and the free stream lines as well as the drag, lift and moment on the sails. He also used the free streamline model to describe the aerodynamics of a two-dimensional flexible sail. His model complemented, (rather than superseded) the aerofoil model, because of the different ranges of validity with respect to the angle of attack. For small angles of attack, where each model can lead to the prediction of sensible solutions, Cisotti's model should be a better representation of reality, because in practice, the stream would begin to separate from the back of the sail.

During the late 1960's Myall and Berger (Ref. 116), concluded that for positive angles of attack, large fluctuations in the pressure distribution are possible. These affect, and are influenced by, the local curvature of the sail, but the variations are usually too small to be detected by the naked eye. They also reviewed the analytical studies to that date concerning the behaviours of flexible sails.

During the early 1970's, Marchaj (Ref. 27) and Kay (Ref. 28), obtained aerodynamic data for triangular yacht sails, but on such a limited scale, (compared with NACA aeronautical data) that it is of little value to sail-type wind-turbine analysis. Also in the 1970's, Tuck and Haselgrove (Ref. 117), extended the Thwaites analysis (Ref. 108) to account for the non-rigid attachment of the sail to the trailing edge. More recently Vanden-Broeck (Ref. 118) investigated the deformation of a two-dimensional sail in a steady potential flow of an incompressible inviscid fluid. The theory thereby developed, follows on from that of Thwaites (Ref. 108) and Nielsen (Ref. 109), and enables one to solve the fully non-linear problem numerically.

7.3 AERODYNAMICS OF WIND-TURBINE FLEXIBLE SAILS

The theoretical analysis of the behaviour of wind-turbine sails differs from that for yacht sails in that more than one sail is involved simultaneously (with consequent interference effects) and the energy harnessed from the wind is manifested as rotational, rather than linear motion. At a specified sail loading (i.e. in a uniform speed with no ground effect) the (exactly) horizontal-axis wind-turbine's sail shape is invariant (with respect to time) and so

FLEXIBLE-SAIL THEORETICAL

Flexible-sail wind-turbine aerodynamics

the aerodynamic theory for rigid bladed wind-turbines (see Chapter 5) is applicable. But this requires that the properties of the sail profile are established. However conventional theory is able to describe the behaviour of flexible sails only if they are effectively "rigid" sails. A variable sail profile rotor is thus not described adequately by existing wind-turbine theories.

The advantages of the flexible sail are its light weight and its flexibility, thereby permitting it to change its profile relative to the wind speed (i.e. to alter the tension experienced by the sail according to circumstances). Unfortunately, existing wind-turbine analyses consider sail (or blade) tensions to be invariable.

7.3.1 Previous Investigations Into The Theoretical Analysis Of Wind-turbine Flexible Sails

Both horizontal (Ref. 119) and vertical (Refs. 21 and 71) axis sail-wing wind-turbines have been investigated. As the sail-wing is essentially a relatively rigid, inflexible body, existing aerofoil theories are applicable to them. Dekker (Ref. 7) and Calvert (Ref. 8) reported studies of Cretan-type, horizontal-axis flexible-sail wind-turbines under laboratory conditions, but without reference to theoretical analyses. Other horizontal-axis wind-turbine investigations (Refs. 4, 5, 6 and 76) have been concerned mainly with "field-testing" the rotors when coupled to water pumps, i.e. they also did not attempt to improve our theoretical understanding of the sail behaviour.

Various vertical-axis wind-turbines of the Chinese (see Chapter 3 section 3.2.1) and Darrieus (see chapter 3 section 3.2.3) types, have sail profiles which vary during each rotation. But again, their aerodynamic behaviour has not been analysed. Sail-type Savonius wind-turbines have recently been investigated (see Chapter 3, sections 3.2.4 and 3.2.5) but their sail profiles were regarded as non-variable — the sails being employed primarily in order to lighten the rotor as well as to reduce the capital cost.

Newman and Ngabo (Ref. 22) studied the behaviour of the flexible sails of a Darrieus-type wind-turbine, and presented an analysis of the change of camber of the sail during rotation. Robert and Newman (Ref. 120) reported the measurement of lift and drag forces on such a sail aerofoil. However, despite numerous experimental investigations of the behaviours of horizontal and vertical-axis, flexible-sail wind-turbines, theoretical analyses of their performances are virtually non-existent.

FLEXIBLE-SAIL THEORETICAL TWO DIMENSIONAL SAIL EQUATION

7.4 TWO DIMENSIONAL SAIL EQUATION

This describes, theoretically, the shape of a wind-filled sail, under specified conditions. The sail considered in Fig. 20, extends from the origin (0,0), denoted by L (i.e the luff), to the point (c,0), denoted by T (i.e. the leach), and at the point (x,z) it has a slope of $\psi(x)$. The sail is represented by a vorticity distribution along the x-axis, where $0 \leq x \leq c$: The vortex strength per unit length is given by $\gamma(x)$ and ξ is used as an x-variable of integration. The uniform wind speed U is inclined at an angle α to the x-axis and the density of the air is ρ .

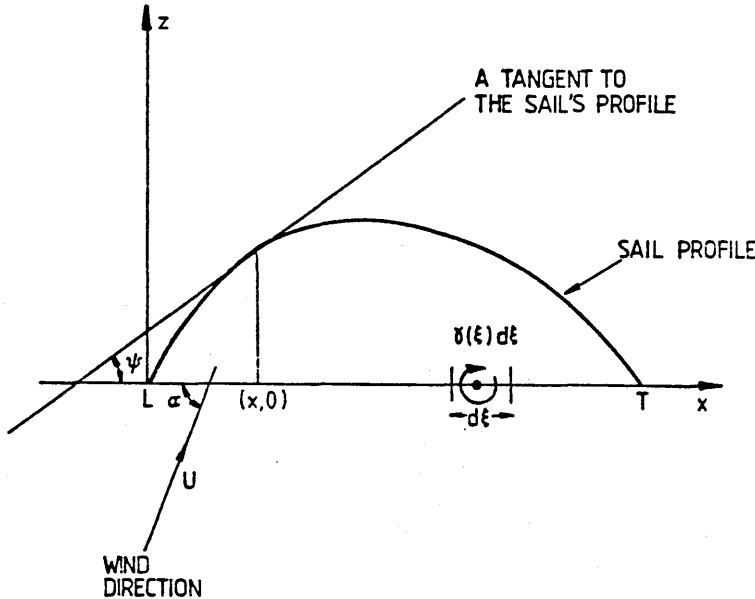


Fig. 20. Sail co-ordinate system and notation.

The usual assumptions of linearised aerofoil theory are made: namely that the camber of the sail and the angle of attack are small.

Using the linear approximation, the lift on an element dx is given by $\rho U \gamma(x) dx$. So the pressure difference Δp between the lower and upper surfaces of the sail is related to the vortex strength

$$\Delta p = \rho U \gamma(x) \quad (79)$$

If the sail is porous and the flow through it is proportional to p , then the through-flow speed in the z -direction is $\sigma(x) \gamma(x)$, where $\sigma(x)$ is the coefficient of porosity.

Therefore the inclination of the air's velocity at the sail, to the x -axis, is $\frac{\psi + \sigma(x) \gamma(x)}{U}$ where ψ is also a function of x .

This must be equal to the inclination induced by the combined stream and vortex sheet, namely

$$\alpha + \frac{1}{2\pi U} \int_{x=0}^{x=c} \frac{\gamma(\xi) d\xi}{\xi - x}$$

FLEXIBLE-SAIL THEORETICAL
Two-dimensional sail equation

Thus by rearranging, we have

$$U \left\{ \alpha - \psi - \frac{\sigma(x) \gamma(x)}{U} \right\} = -\frac{1}{2\pi} \int_{x=0}^{x=c} \frac{\gamma(\xi) d\xi}{\xi - x} \quad (80)$$

This is the aerodynamic equation connecting the shape of the sail to the pressure distribution over it.

Neglecting viscous shear forces, the steady-state condition implies that the tension T , experienced by the sail (see Fig. 21) must be constant.

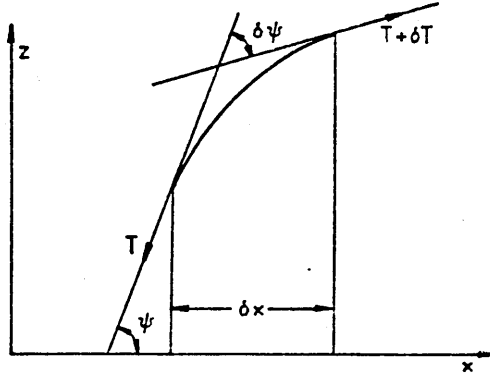


Fig. 21. The tension distribution experienced by a sail element

The condition of normal static equilibrium then requires

$$\Delta p dx = -T d\psi \quad (81)$$

Thus from equation (79)

$$\rho U \gamma(x) = -T \frac{d\psi}{dx} \quad (82)$$

Substituting from equation (82) into equation (80), gives

$$\alpha - \psi + \left(\frac{\sigma(x) T}{\rho U^2} \right) \frac{d\psi}{dx} = \frac{1}{2\pi} \frac{T}{\rho U^2} \int_{x=0}^{x=c} \frac{\frac{d\psi}{d\xi} d\xi}{\xi - x} \quad (83)$$

This is the basic equation for a two-dimensional porous sail.

To satisfy the Kutta-Joukowski condition that the flow leaves the trailing edge smoothly, then

$$\gamma(c) = 0 \quad (84)$$

Also, as L and T have been defined to lie on the x -plane, the slope of the sail must satisfy

$$\int_{x=0}^{x=c} \psi dx = 0 \quad (85)$$

FLEXIBLE-SAIL THEORETICAL

Two-dimensional sail equation

The problem of the two-dimensional sail then reduces to the solution of equation (83) subject to the constraints imposed by conditions (84) and (85).

Equation (83) relates to one sail only. For a wind-turbine with several sails, equation (83) would need to be modified to include additional "coupling terms" representing the mutual interference of the sails.

Once the wind-turbine sail shape is known, existing wind-turbine theory (see Chapters 5 and 6) could then be used to analyse, theoretically, the flexible-sail wind-turbine's performance characteristics.

7.5 FUTURE DEVELOPMENTS

Both the horizontal and vertical-axis sail-type wind-turbines are complicated to analyse mathematically. For the horizontal (or near horizontal) axis rotor in a uniform constant air stream, the sail shape remains invariant throughout the rotation, but the sail profile varies according to the distance from the central axis. The sail profile of the vertical-axis wind-turbine in a uniform wind with no "ground effect", is the same for the whole of one sail at one particular rotary position, but it varies as the sail rotates around the vertical-axis. The theoretical understanding of the behaviour of flexible-sail wind-turbines should be improved via the parallel studies of these two distinctly different modes of sail operation.

Although available wind-turbine theory is valid for specific sail profiles, that corresponding understanding for variable-sail profile wind-turbines does not exist. However the analysis of the behaviour of yacht sails provides a significant starting point concerning the theoretical understanding of wind-turbines with flexible sails. Nevertheless, there is now an urgent need for even a basic elementary theory concerning the performance of flexible-sail wind-turbines, to be developed. Only then will optimal designs of flexible-sail wind-turbines, appropriate to the various prospective applications (see Chapter 3 section 3.5) emerge.

CHAPTER 8

HORIZONTAL-AXIS WIND-TURBINE

The horizontal-axis wind-turbine consisted of a rotor to which were attached sails and appropriate measuring equipment.

8.1 THE ROTOR

A small scale rotor was required in order to complement the existing 0.84 m diameter wind tunnel facility. Thus it was decided, for this investigation, to utilise a 0.64 m diameter cycle wheel as the rotor — because of its availability and lightweight, yet strong structure. The sails were easily attached to the rotor spokes, their angles and areas simply varied. Tip-fins were readily fixed to the rim in a variety of different inclinations and positions, and centre-bodies were simply fastened to the rotor.

8.1.1 The Sails

Previous research on sail-type wind-turbines (Refs. 7, 8 and 121) suggested that the rotor should have a relatively large number of sails. Accordingly 9 sails were used throughout the series of tests. This facilitated the fixing of the sails to the rotor spokes (36 spokes, therefore 4 spokes per sail).

8.1.1.1 Sail Angle -

Studding (6 ba) was used so as to simply and easily change the sail angle (β). The final, optimised rotor would use either elastic sail attachments which yield in high winds, or alternatively shock cord, to provide a degree of self-regulation in high speed winds.

This cord (see Fig. 22) would break (at point A) in high speed winds, resulting in the second, stronger cord (cord B) holding the sail at a far greater sail angle. This large angle would thus aid the sail to "spill the wind" so reducing the rotor's rotational speed.

HORIZONTAL-AXIS WIND-TURBINE

The rotor

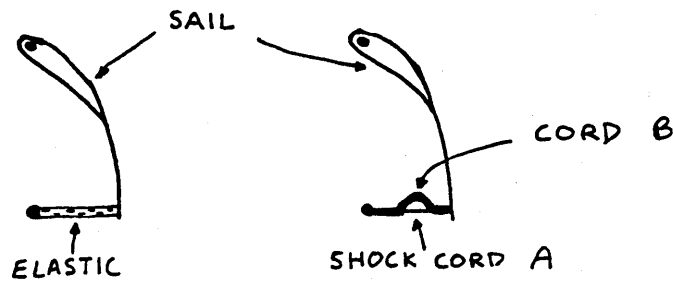


Fig. 22. (a) Elastic sail attachment; and (b) shock cord.

8.1.1.2 Spoke Angle -

The spoke angle was at a constant 7.5 degrees, thus the sails were inclined at 7.5 degrees to the rotor plane.

8.1.1.3 Solidity Ratio -

The optimal solidity (see Chapter 5, section 5.2.5) was determined from the first series of tests, (see Chapter 12 section 12.2.1). A relatively large solidity of 95 per cent was thus used for all subsequent tests.

8.2 POWER AUGMENTATION

8.2.1 The Shroud

Substantial power enhancement advantages for a wind-turbine can be realised by the use of a shroud (Ref. 122). Thus to improve the performance of the flexible sail wind-turbine, the rotor was enclosed within the wind tunnel. This duct thereby acted as a shroud, (see Fig. 22).

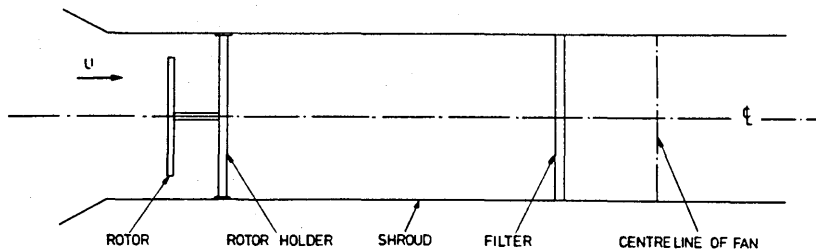


Fig. 23. Schematic representation of the location of the tested wind-turbine (of 0.64 m diameter) within the test tunnel (of 0.84 m diameter).

HORIZONTAL-AXIS WIND-TURBINE Power augmentation — shroud

The presence of a shroud leads to a pressure rise down-stream of the rotor at the expense of the kinetic energy of the flow. This enables the rotor to engorge air from a free-stream tube area far greater than the area of the rotor. Consequently, the flow wind velocity through the rotor is typically between 20 and 60 per cent greater than the free-stream velocity, whereas it would be about 67 per cent less for the unshrouded assembly (Ref. 123). The flow field around a rotor operating in the open atmosphere is shown schematically in Fig. 24.

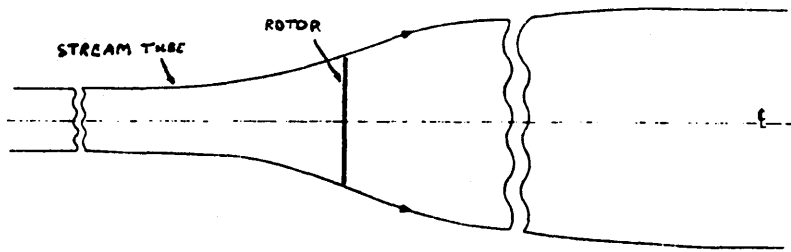


Fig. 24. Stream tube for air flowing through a wind-turbine in free air conditions.

As power is withdrawn from the wind stream, the axial flow velocity decreases as the air passes through the rotor. Applying the continuity law for incompressible flow to this stream tube, it can be shown (Ref. 124) that $A_1 < A_r$, whereas the amount of energy theoretically available at the rotor for given conditions, of U and A_r , where $A_r = \pi R^2$, is, (see also Chapter 5, section 5.1)

$$P = \frac{1}{2} \rho U^3 \pi R^2 \quad (2)$$

A simple and effective way to increase the value of A_1 , for a given free-stream condition and rotor geometry is therefore to enclose the rotor within a shroud.

The maximum attainable power coefficient for an unshrouded horizontal-axis rotor (see Chapter 5, section 5.3.1) is;

$$P = 0.593 \times \frac{1}{2} \rho U^3 R^2 \pi \quad (30)$$

that is, a maximum power coefficient of, $C_{p_{\max}} = 0.593$.

This maximum power coefficient is sometimes termed the Betz coefficient.

HORIZONTAL-AXIS WIND-TURBINE Power augmentation — shroud

Tests (Ref. 125) have shown that the shrouded rotor can extract approximately twice as much power as an ideal wind-turbine of the same diameter under the same free-stream conditions but without any duct present. This is described as the system having an augmentation factor of 2, where the augmentation factor is defined as;

$$\frac{P}{P_{\max}} = \left(\frac{P}{\frac{1}{2} \rho U^3 \pi R^2} \right) \left(\frac{1}{0.593} \right) \quad (86)$$

P, being the power harnessed by the wind-turbine and $P_{\max}$, the theoretical maximum power for a horizontal-axis wind-turbine working in the open atmosphere.

By utilising the shroud, the Betz coefficient no longer applies, so enabling shrouded wind-turbines to have power coefficients exceeding unity. Subsequent research (Refs. 9, 10, and 126) suggested that augmentation factors of 3 are possible with an optimal shroud geometry.

First generation shrouded wind-turbines proved unacceptable because they were designed with length-to-diameter ratios, for the shroud, of at least 7. Recent work on aerogenerator shrouds (Refs. 124 and 127) clearly indicated that it is possible to design acceptable shrouds with a total length-to-diameter ratio of about 3.

The shroud also offers some measure of protection to the wind-turbine and so should lead to reduced costs. For domestic applications it is probable that wind-turbines (of say 2.5 m diameter) will need shrouds passing through attic spaces. This will make them more architecturally acceptable as well as lead to less television interference — a problem which could result in contention if conventional wind energy conversion systems become prolific (Ref. 128). Access to the wind-turbine via the attic space would then also be facilitated.

To minimise structural and maintenance problems it is probable that the axis of the shroud should be fixed in the direction of the prevailing wind. This would not significantly reduce its power output, as the concentrator at the entrance of the shroud enables the rotor to capture air from an approximately ± 30 degree inclination from the set direction.

8.2.2 Tip-fins

The theory (see Chapter 5, section 5.3.1) predicting the maximum power coefficient for wind-turbines is only valid for ideal rotors applying a steady axial force to the air stream. Real wind-turbines, that produce radial, as well as axial forces, are not accounted for by this analysis and they may have much greater power outputs than the one-dimensional theory suggests.

HORIZONTAL-AXIS WIND-TURBINE Power augmentation — tip-fins

The shrouded wind-turbine — a rotor surrounded by what is essentially a cylindrical circular wing that directs an aerodynamic "lift" force radially inwards — is capable of at least trebling the power output of a wind-turbine (see section 8.2.1). As a reaction to the "lift" directed towards the shroud centre-line, a cross-wind force acts upon the air, so deflecting the flow outwards, causing its stream tube to widen down-wind of the shroud (see Fig. 25).

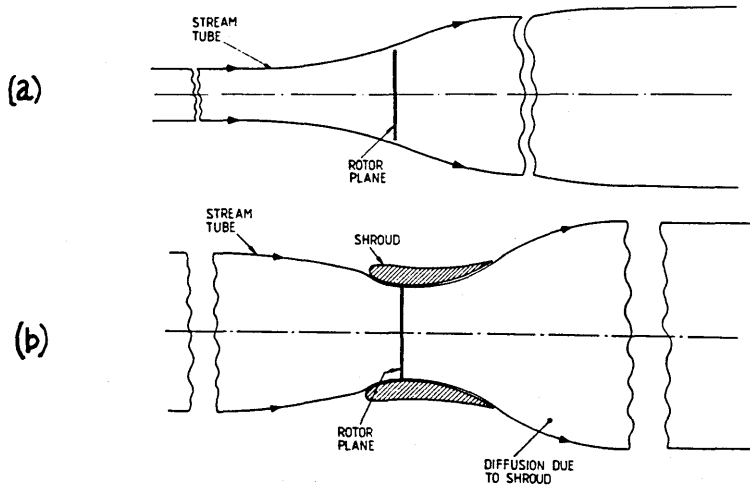


Fig. 25, (a) Stream tube for air flowing through a conventional horizontal-axis wind-turbine, (b) Stream tube for air flowing through the wind-turbine of Fig. 25 (a) which is now enclosed within a shroud.

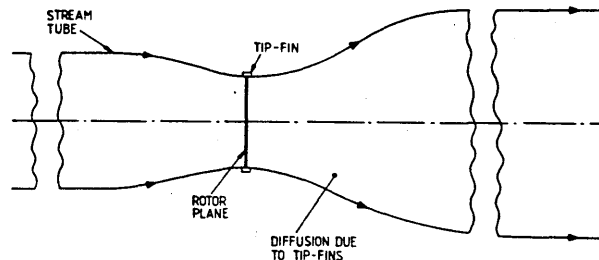


Fig. 26. Stream tube for air flowing through a tip-fin augmented version of the rotor of Fig. 25(a).

Although the shroud is eminently capable of augmenting wind-turbine power outputs, it is relatively expensive, so inhibiting its future widespread incorporation in cheap wind-turbine systems.

Van Holten (Ref. 129), from data obtained with a simulated propeller-type wind-turbine, showed that the diffusion ratio is dependent upon the mean radial force so exerted by the wind per unit length of the circumference of the rotor plane. This suggests that to achieve diffusion of the flow, a full shroud may not be required. Replacing the shroud by tip-fins (which are also referred to as tipvanes) concentrates the cross-wind forces on the aerodynamic surfaces near the circular periphery of the wind-turbine.

HORIZONTAL-AXIS WIND-TURBINE
Power augmentation — tip-fins

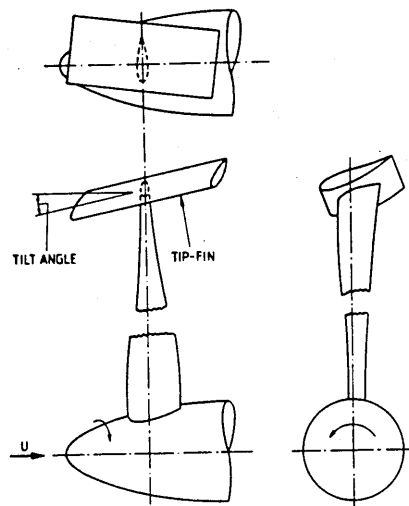


Fig. 27. Tip-fin (tipvane) on a rigid propeller, as conceived by van Holten (Ref. 129).

This arrangement, shown in Fig. 27, causes a deflection of the air-stream in a manner analogous to that occurring in shrouded wind-turbines.

The power enhancement is greater for a shrouded rotor than for a rotor with tip-fin augmentors. This occurs because the drag forces on the shroud do not adversely affect the power output of the wind-turbine. However, with the tip-fin augmented wind-turbine, induced and viscous drag forces ensure that the power augmentation capability is less than that achievable with the shrouded wind-turbine.

By utilising relatively inexpensive aerodynamically-shaped tip-fins, the induced drag can be made negligible (Ref. 2). As the cross-wind forces do no work on the fluid, no energy is lost to establish a force field, and so no torque is required to drive the tipvane (Ref. 129). This implies that they need not experience induced drag. But the drag is also dependent upon tip-fin shape, as well as the "tilt" angle (see Fig. 27).

The basic tip-fins tested here were not aerodynamically shaped and so the induced drag was not negligible. Despite this, these basic cheap fins were capable of significantly increasing the wind-turbine's power harnessing capabilities.

8.2.3 Centre-bodies

In order to capture a greater proportion of the energy available in the wind, and so augment wind-turbine power outputs, various means have been investigated. The centre-body is one such device for horizontal-axis wind-turbines, and other types of deflectors can be profitably employed with vertical-axis rotors.

HORIZONTAL-AXIS WIND-TURBINE

Power augmentation — centre-bodies

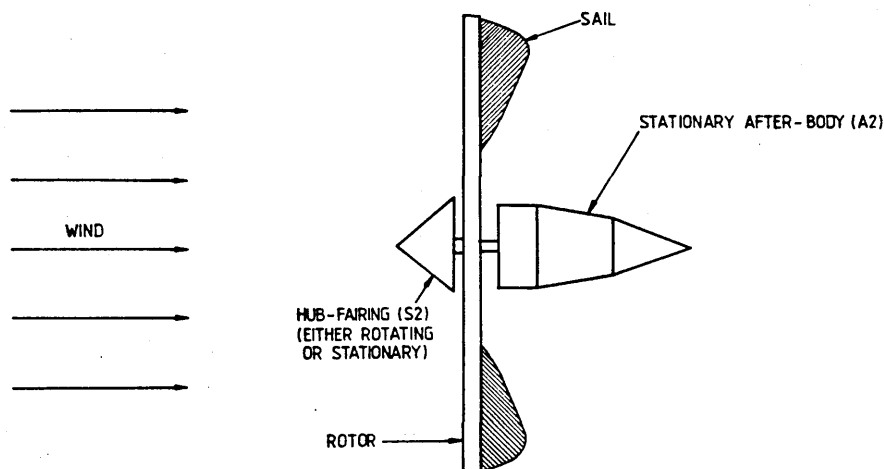


Fig. 28. Centre-body augmented wind-turbine.

The centre-body, shown in Fig. 28, consists of a hub-fairing and an after-body. The hub-fairing generally rotates (with the rotor) whereas the after-body is usually held stationary and encloses the "power-take-off" equipment. The centre-body's function is to interfere favourably with the wind passing through the rotor, thereby increasing the speed of air impingement (and hence the couple imposed) upon the sails, which are predominantly near the outer rim of the rotor.

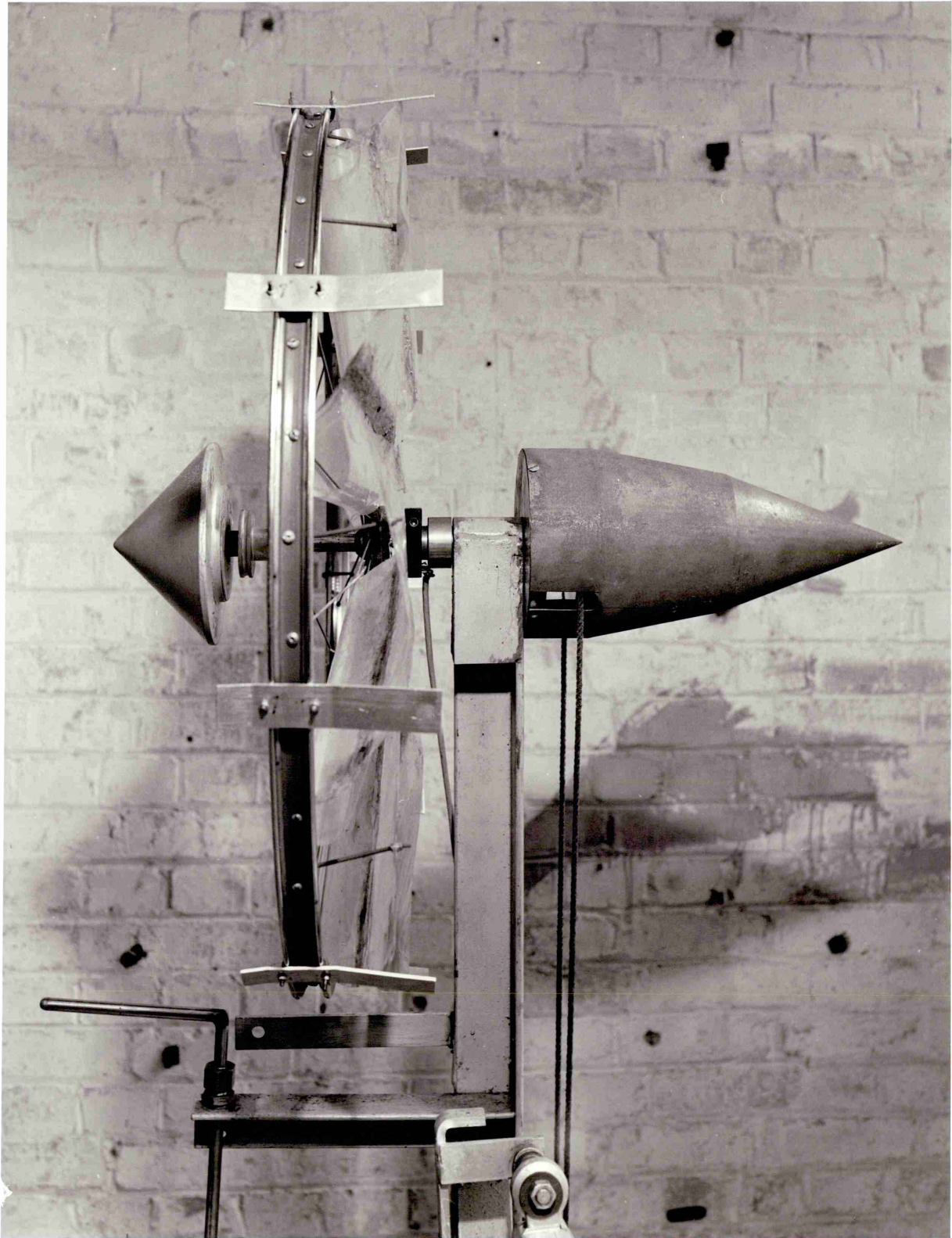
If a streamlined body is introduced into a uniform air flow, the average local velocity of the stream is increased as the air passes over that body. Thus placing a streamlined hub-fairing symmetrically about the central axis of a wind-turbine should result in greater air pressures being experienced on the "working sections" of the rotor sails. That is, the fairing deflects air that would normally flow through the "hub-section" of the rotor, outwards onto the sails, where such momentum transfer will have a greater effect in producing rotation. Thus a centre-body will increase the mean mass flow rate of air through the sails of the wind-turbine, so enhancing the amount of wind energy harnessed by the sails.

Theoretical analyses of rigid (or almost rigid) propeller-type wind-turbines (Refs. 130 and 131) suggest that there is little advantage to be gained by using centre-bodies (e.g. a spinner and a stationary after-body) to augment the power outputs. The major reasons for this assertion are alleged to be:

1. the hub-fairing increases the the local axial component of relative velocity; and
2. the frictional drag produced by the hub-fairing decreases the local tangential component of relative velocity.

Plate 1

Tip-fin and centre-body augmented horizontal-axis wind-turbine.



HORIZONTAL-AXIS WIND-TURBINE

Power augmentation — centre-bodies

Both these component changes tend to increase the local aerofoil angle of attack beyond the stall angle, so adversely affecting the wind-turbine's power harnessing capabilities. The frictional effect is believed to be less than that due to the increase in the local axial relative velocity component. However, previous experimental investigations have not resulted in unanimous conclusions. During the nineteen-thirties, a team from New York University (Ref. 132) working on the "Smith-Putnam" wind-turbine (Ref. 55) concluded that a hub-fairing was disadvantageous. More recently Blaha (Ref. 11) obtained considerable power increases by incorporating centre-bodies on a prototype wind-turbine, but there was some doubt as to whether his procedure would "scale-up" for larger turbines.

Because air is deflected by the hub-fairing towards the "working zone" of the sail (i.e. near the periphery of the rotor), there will be a corresponding increase in rotor tip losses. These occur due to a reduction in lift at the sail tips, where the sail cannot support the lifting pressure differential between the upper and lower surfaces of each sail. The losses depend directly upon the sail loading (i.e. the magnitude of the pressure differential) and are expected to increase with the hub-fairing diameter.

Thus it is probable that centre-bodies will have the greatest effects on wind-turbine performance characteristics, if employed with appropriately designed tip-fins.

8.2.4 Tip-fin And Centre-body Combined

Tip-fins, i.e. small, cheap, basic auxiliary surfaces attached to the periphery of a wind-turbine (see Platel, fig 2) are capable of considerably increasing the power outputs of small, horizontal-axis sail-type wind-turbines. Augmentation is achieved by the tip-fins aiding diffusion of the exhaust air down-stream and by reducing the sail tip losses, so increasing the wind velocity through the rotor and thereby harnessing more power from the wind.

These tip losses (i.e. reductions in the circulation of the air near the outer edge of each sail) occur due to the interaction of the shed vorticity with the air flow near the sail's outer edge. As the kinetic energy of the wind is converted to kinetic energy of the rotating sails of the wind-turbine, a pressure difference occurs between the two sides of each sail. This results in air flowing round the ends of the sails (both at the outer and inner edges of the sails) from the high pressure side to the low pressure side, and hence the establishment of trailing vortices.

HORIZONTAL-AXIS WIND-TURBINE

Power augmentation — tip-fin and centre-body combined

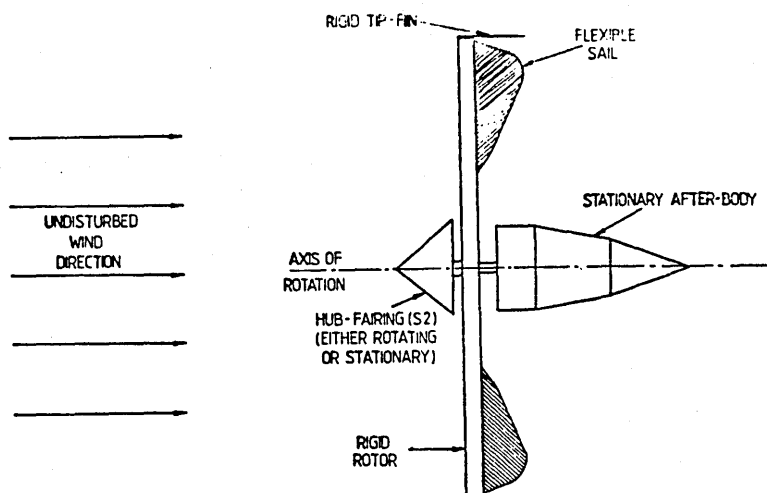


Fig. 29. Centre-body and tip-fin augmented wind-turbine.

Tip-fins not only reduce this air flow at the outer edge of the sail, but also serve to diffuse the air down-stream of the wind-turbine. Thus they act in a similar manner to that of the shrouded (Ref. 126) or diffuser-augmented (Ref. 10), wind-turbine.

The centre-body consists of a hub-fairing and an after-body (see Fig. 29). To improve the wind-turbine's performance, it is customary for the hub-fairing to be allowed to rotate with the turbine, whereas the after-body is generally held stationary.

The hub-fairing positioned symmetrically about the horizontal axis of the wind-turbine, deflects the wind flow towards the sails, all of which are positioned near the periphery of the rotor. It thereby increases the speed of the air impingement upon the flexible sails, so resulting in greater torques being experienced by the turbine.

Hub-fairings also act in a manner analogous to tip-fins in that they reduce the sail tip losses, but now for those edges near the hub section of the rotor. In other words, because of the presence of the hub-fairings, the air-flow from one side of a sail to the other, at its edge, near the wind-turbine's central axis, is diminished.

Because the hub-fairing deflects air towards the more effective working sections of the sails there will be a corresponding increase in tip losses for the outer edges of the wind-turbine. This occurs because the hub-fairing reduces the hub losses by deflecting the incoming air outward to the periphery of the rotor — i.e. towards the more effective working sections of the sail. This increased air flow rate at the circumference of the rotor consequently leads to slightly higher tip losses there. However these tip losses can be reduced by employing tip-fins, of the form described earlier (see section 8.2.2).

HORIZONTAL-AXIS WIND-TURBINE

Power augmentation — tip-fin and centre-body combined

Thus the combination of a centre-body and a set of tip-fins can have the effect of reducing the sail tip losses both for the sail edges near the hub and near the periphery, so increasing the wind-turbine's power harnessing capabilities.

8.2.5 The Economic Viability Of Power Augmentors.

It is sometimes implied that, if the extra financial expense incurred upon the augmentation devices were used instead, to pay for an increase in the wind-turbine's diameter, then the performance of the power augmented wind-turbine would compare unfavourably with that of the unaugmented larger rotor. Whilst it is arguably true for the shrouded wind-turbine it is false with respect to the cheap, basic augmentation devices (i.e. tip-fins and centre-bodies), tested in this project. These represent only a small proportion of the wind-turbine's costs and their capabilities of enhancing power outputs are far greater than could be achieved if the extra finance is, at the time of construction, devoted to an increase in the rotor diameter.

CHAPTER 9

VERTICAL-AXIS WIND-TURBINE

The major disadvantage of horizontal-axis wind-turbines is their inability to harness the wind from all directions. Vertical-axis wind-turbines are non-directional and so do not require any orientational devices to keep them turned into the wind.

9.1 ADVANTAGES OF VERTICAL-AXIS WIND-TURBINES

Vertical-axis wind-turbines have the following advantages:-

1. most are self starting;
2. each system is intrinsically non-directional, i.e. the rotor does not have to be appropriately located with respect to the wind direction: such a rotor can thus harness gusts emanating from any direction;
3. only a single rotating shaft is required for each such wind-turbine: this can be used to transmit power, and thus the pump or gearbox can be located at ground level; and
4. the mechanical stresses imposed on the blades (or sails) are reduced relative to those encountered with horizontal-axis wind-turbines of similar power output.

9.2 THE SAVONIUS WIND-TURBINE

Savonius developed the wind-driven rotor, that subsequently bore his name, during the 1920's (Ref. 13) as a modification of the Flettner rotor (Ref. 39). The latter consisted of a vertically mounted cylinder, which, when rotated in a wind stream (by means of a diesel engine) produced a lateral thrust. This thrust — i.e. the Magnus effect (Ref. 60) — was created by the asymmetrical streaming of the wind around the rotor, and was successfully used to propel a large ship across the Atlantic, see Chapter 2 section 2.2.2.

VERTICAL-AXIS WIND-TURBINE Savonius wind-turbine

Savonius modified Flettner's rotor by splitting the cylinder in half along its central axis and displacing the two semi-cylindrical surfaces sideways, so forming, in plan view, a rotor that resembled the letter S, see Fig. 30. This allowed the rotor to be driven by the wind, thereby dispensing with the diesel motor required to rotate Flettner's cylinders.

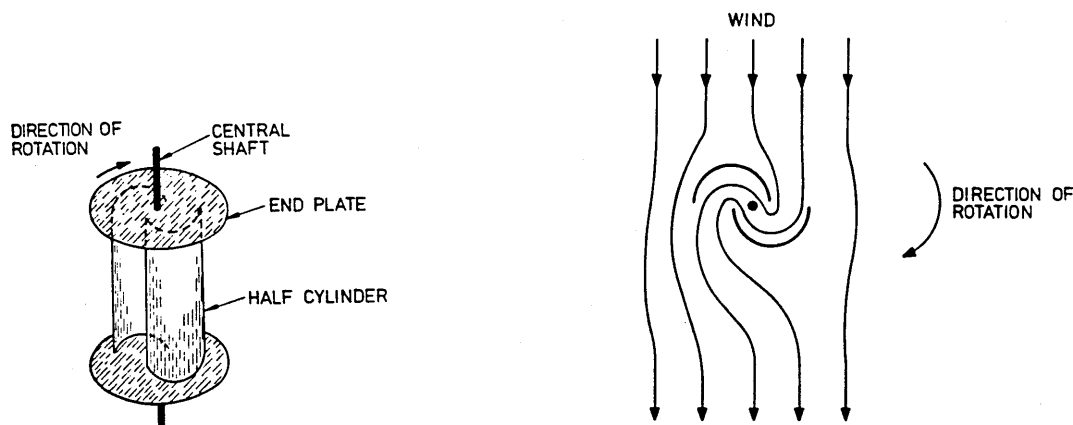


Fig. 30. The conventional Savonius wind-turbine

A gap between the turbine and the semi-cylindrical cups was allowed so that some of the air striking one cup would flow through the central gap and so provide a useful thrust on the other cup. This also resulted in a reduction of the overall drag because the air pressure down-stream of the rotor was higher than if there were no central gap. The speed of rotation was also greater. The Savonius rotor developed larger lateral (i.e. propulsive) forces than could be obtained with a comparable sized Flettner rotor. However the Savonius rotor has survived despite, rather than because of, these lateral forces.

The Savonius or, S, rotor has since been used successfully for a variety of diverse applications — including centrifugal ventilators, ocean current meters, exhaust fans, harnessing tidal power, as well as for pumping water and for generating electricity.

The Savonius wind-turbine possesses all the advantages of the vertical-axis wind-turbine, (see section 9.1), but unfortunately also suffers from the following disadvantages:-

1. a high ratio of weight to projected rotor area: this limits the usefulness of the design to relatively small diameters;
2. compared with high speed propeller-type rotors, the Savonius wind-turbine has relatively low power coefficients attainable over a narrow range of tip-to-wind speed ratio; and
3. the system is prone to vibration.

VERTICAL-AXIS WIND-TURBINE
Savonius wind-turbine

However, using flexible sails rather than rigid "blades", would diminish the severity of the first disadvantage and the importance of the second disadvantage would be greatly reduced by designing the rotor to operate in low-speed winds ($< 5 \text{ ms}^{-1}$) and to be manufactured cheaply. The relatively light weight and low speed of a flexible-sail rotor would also tend to reduce the likelihood of vibrational damage and hence lessen maintenance problems.

9.3 PROPOSED SAIL VERSION OF THE SAVONIUS-TYPE WIND-TURBINE

In an attempt to improve the performance characteristics of the Savonius wind-turbine, sails rather than rigid blades were proposed. The sail-type wind-turbine differs from those previously investigated in India and in the Netherlands (see Chapter 3 sections 3.3.3 and 3.3.4) in that the flexible sail rotor is designed so that the sails change their profile dependent upon their position relative to the wind.

The employment of such sails would both

1. reduce the overall weight of the wind-turbine, and
2. when used with support rods, enable the sails to take up shapes dictated by their position relative to the wind strength and direction.

Initially the design proposed here had three, straight, rectangular sails, but subsequently curved sails were adopted to facilitate starting and to harness greater energy from the wind. Thus the wind-turbine developed is basically a Savonius-type wind-turbine.

This low cost, easily constructed and maintained system is much lighter than the conventional Savonius rotor and so it extracts energy successfully from relatively low speed winds. The profile of each sail depends upon its position relative to the wind direction (see Fig. 31).

During the momentum-capture phase of operation, each flexible sail forms a more-cupped shape thereby acquiring greater rotational torque. However, when each sail is rotating against the wind, it is forced back onto a series of rods, and these rods thus define the sail shape. The centrifugal force tends to throw the sail sheet outwards and so it presents a reduced resistance to the wind (see Fig. 31). Thus the sail-type Savonius rotor does not have one distinct sail geometry, as occurs with the more conventional rigid Savonius wind-turbine, so it is suggested, it can acquire higher rotational speeds and harness more energy from the same wind.

VERTICAL-AXIS WIND-TURBINE Sail-type Savonius wind-turbine

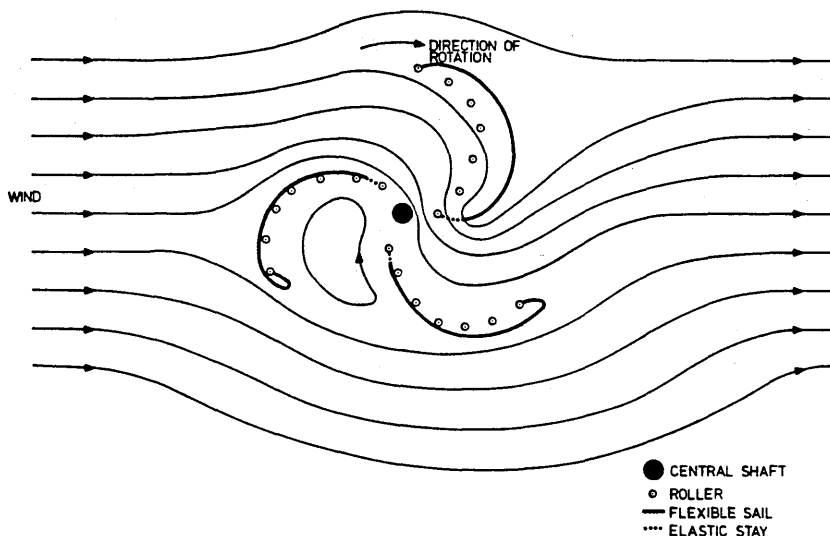


Fig. 31. The three flexible-sail Savonius-type vertical-axis wind-turbine: schematic representation of the flow and of the sail profiles.

Excessive speed is a problem with the conventional Savonius wind-turbines, because of the large mechanical stresses which thereby ensue. Thus some form of governor or self regulator is often needed. However by fastening the flexible sails to the three inner most rollers of the proposed rotor by means of elastic stays or shock cord, designed to partially yield in high wind speeds, provides a considerable degree of self-regulation so preventing the system from rotating too quickly. Then the central gap for the passage of air would be far greater than that shown in Fig. 31. As the wind speed increases, the sail in the momentum-capture phase of operation is forced outwards so leading to more of the air spilling through the wider central passage. This results in less drag being encountered and lower rotational speeds being attained.

Support rod diameter, spacing between the rods and sail flexibility would need to be optimised so that centrifugal action throws the sail outwards, rather than allowing the wind to shape the sail into "cups" between the support rods. The profile of the series of rods, (which defines the shape of the sail when the wind and sail directions are opposing), the free (i.e. momentum capture) sail shape and the sail pitch would also need to be designed to maximise the harnessing rate of wind energy for each particular site.

9.3.1 Power Augmentaion Devices

Flettner and Savonius both realised that by using end-plates (see Fig. 30) greater rotational speeds were attainable than with rotors without end-plates (see Chapter 6, section 6.4.1). Extending this principle by shrouding the Savonius rotor could further enhance its performance, thereby entraining a greater mass flow of air within the rotor, so enabling more power to be extracted.

VERTICAL-AXIS WIND-TURBINE
FINALLY CHOSEN DESIGN

9.4 FINALLY CHOSEN DESIGN

Once the optimal sail profiles and rotor dimensions for a particular wind regime are determined, the wind-turbine could be modified to reduce the constructional skills required. The supporting frame could be fabricated using wood and the metal bearings replaced by oil-impregnated hardwood ones. This would make the wind-turbine more readily acceptable in rural areas of the Third World (see Chapter 4), where sophisticated technology is unavailable and likely to remain so for a considerable time. Despite these modifications, which may lessen the overall wind-turbine efficiency, the construction costs would be greatly reduced and simple hand-tools could be employed, so making the Savonius wind-turbine more appropriate to less-developed countries.

Alternatively, in areas where rudimentary-equipped workshops exist with welding facilities, steel frameworks and bearing assemblies could be profitably employed.

CHAPTER 10

WATER PUMPING

Owing to the varying torques and power outputs generated from wind-turbines, the pumps to be coupled to them should be able to operate effectively under these conditions. However, a conventional pump possesses almost a fixed inertia and is thus designed to operate within a very limited range of rotational speeds. This may therefore inhibit its effectiveness for use with wind-turbines.

10.1 WIND-TURBINE AND PUMP MATCHING

For the optimal harnessing of the wind's energy in order to pump water, the torque characteristics of the pump and the wind-turbine should be matched. Sail-type wind-turbines possess a nearly parabolic relationship between their power coefficient (C_p) and their tip-to-wind speed ratio (λ). This gives an approximately linear relationship between the torque coefficient (C_q) and the tip-to-wind speed ratio. These relationships are shown in Fig. 32.

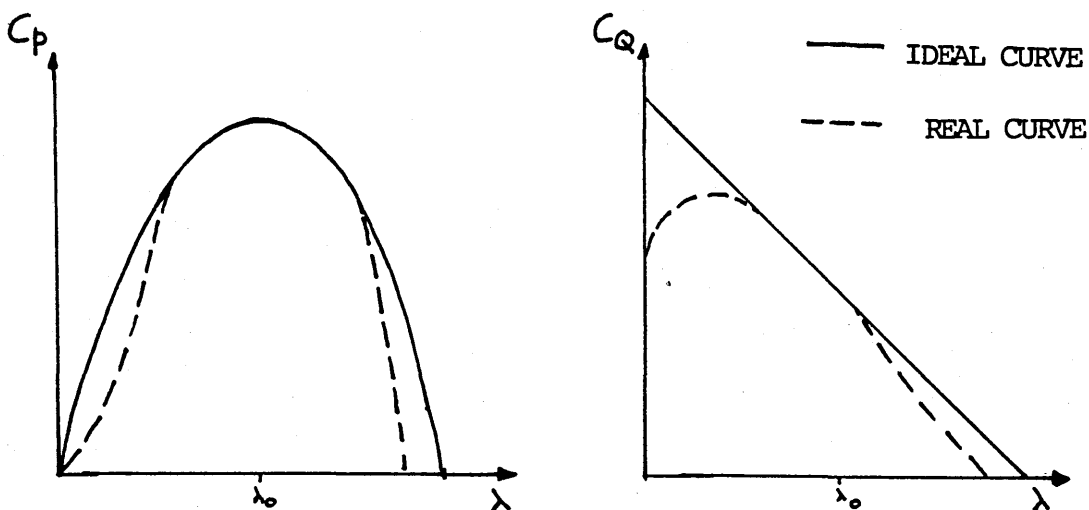


Fig. 32 (a) Power coefficient; and (b) torque coefficient; of a sail-type wind-turbine versus its tip-to-wind speed ratio.

WATER PUMPING

Pump-matching

In the following section the theoretical analysis of matching a wind-turbine with a linear C_Q - λ characteristic to a pump with a constant torque is presented. In reality the torque of a peristaltic pump varies during rotation and, see Fig. 32, the real C_Q - λ characteristics are not linear. Nevertheless this idealised theoretical solution to the matching of turbine and pump provides a significant insight into the operation and efficiency of a wind-turbine and pump combination.

Assuming that the wind-turbine has a quadratic C_P - λ characteristic, the following can be derived.

$$Q_{\text{ROTOR}} = C_Q \frac{1}{2} \rho U^2 A R \quad (87)$$

$$P_{\text{ROTOR}} = C_P \frac{1}{2} \rho U^3 A \quad (88)$$

and if $\lambda = \lambda_0$, for $C_P = C_{P_{\text{max}}}$, then,

$$C_Q = \frac{-C_{P_{\text{max}}}}{\lambda_0} \left\{ \frac{\lambda}{\lambda_0} - 2 \right\} \quad (89)$$

$$C_P = -C_{P_{\text{max}}} \left\{ \left(\frac{\lambda}{\lambda_0} \right)^2 - 2 \frac{\lambda}{\lambda_0} \right\} \quad (90)$$

Assuming that the pump operates at an efficiency of 100 per cent and has a constant torque, then

$$Q_{\text{PUMP}} = \text{constant}$$

$$P_{\text{PUMP}} = Q_{\text{PUMP}} \omega \quad (91)$$

We assume that the wind-turbine and pump combination is designed so that the maximum power coefficient of the rotor ($C_{P_{\text{max}}}$) occurs at a certain wind speed (u_0), operating at a tip-to-wind speed ratio of λ_0 .

The following torque will be developed by the wind-turbine in a uniform wind speed of u_0 .

$$Q(u_0) = \frac{C_{P_{\text{max}}}}{\lambda_0} \frac{1}{2} \rho A R u_0^2 \quad (92)$$

This torque remains constant for all wind speeds, as this is the torque required by the pump.

From equations (87) and (89) an expression for the torque developed by the rotor can be given as

$$Q(u) = \frac{-C_{P_{\text{max}}}}{\lambda_0} \left(\frac{\lambda}{\lambda_0} - 2 \right) \frac{1}{2} \rho U^2 A R \quad (93)$$

Equating equations (92) and (93), gives

$$\frac{\lambda}{\lambda_0} = 2 - \left(\frac{u}{u_0} \right)^{-2} \quad (94)$$

Since $\lambda = \frac{\lambda R}{u}$ and $\lambda_o = \frac{\lambda_o R}{u_o}$ then

$$\frac{\lambda_h}{\lambda_o} = 2 \left(\frac{u}{u_o} \right) - \left(\frac{u}{u_o} \right)^{-1} \quad (95)$$

As $P = Q \lambda_h$, where Q is constant, from equation (95) we have,

$$\begin{aligned} \frac{P}{P_o} &= \frac{Q}{Q_o} \frac{\lambda_h}{\lambda_o} = \frac{\lambda_h}{\lambda_o} \\ &= 2 \left(\frac{u}{u_o} \right) - \left(\frac{u}{u_o} \right)^{-1} \end{aligned} \quad (96)$$

By plotting $\frac{P}{P_o}$ as a function of $\frac{u}{u_o}$, Fig. 33 can be obtained.

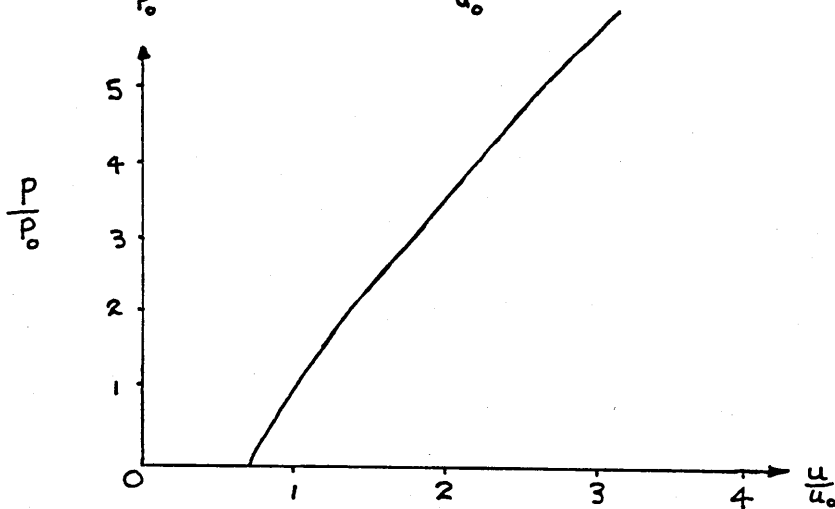


Fig. 33. The pumping power of a wind-turbine and pump combination, as a function of wind velocity. (Pumping power and wind velocity are expressed dimensionlessly in terms of the design parameters P_o and u_o respectively).

From equations (90) and (94) we can derive,

$$\begin{aligned} \frac{C_p}{C_{pmax}} &= \left\{ \left(\frac{\lambda}{\lambda_o} \right)^2 - 2 \left(\frac{\lambda}{\lambda_o} \right) \right\} \\ &= 2 \left(\frac{u}{u_o} \right)^{-2} - \left(\frac{u}{u_o} \right)^{-4} \end{aligned} \quad (97)$$

This is shown graphically in Fig. 34.

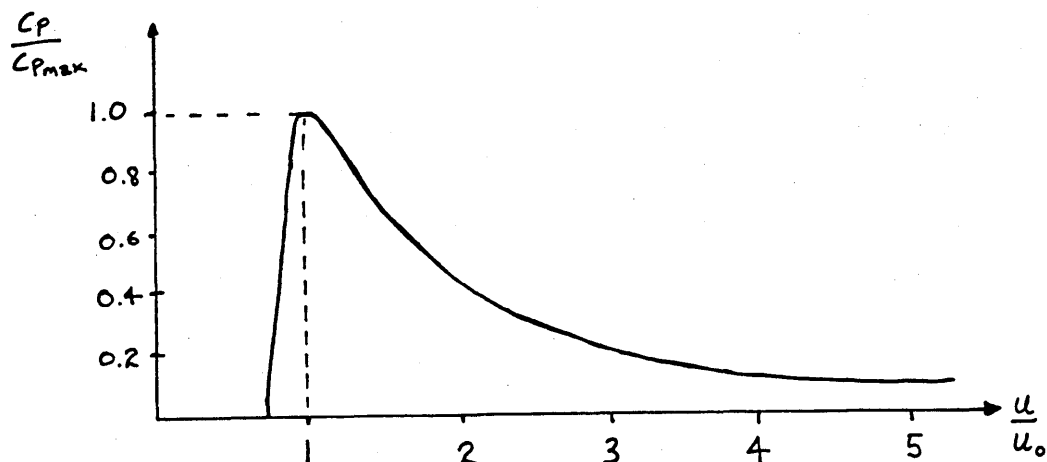


Fig. 34. The power coefficient of a wind-turbine pump combination against the non-dimensional wind speed parameter.

From Fig. 34, it is apparent that a wind-turbine with a quadratic power coefficient versus tip-to-wind speed ratio relationship coupled to a constant torque pump, works at relatively low efficiencies. The lower the efficiency, the higher the wind speed. From equation (96) if $u > \frac{1}{2}\sqrt{2}u_0$, then the wind-pump will pump water.

Whilst overall efficiencies are relatively low at high wind speeds, these inefficiencies can be tolerated. The wind-pump's design operating speed would be determined by the wind regime of the appropriate physical site and thus would be designed to pump the required quantity of water in this particular régime. Thus low efficiencies in high wind speeds — i.e. when the wind-pump would (by definition) be raising larger quantities of water than required — are relatively unimportant. Nevertheless, it appears that for optimal matching of the wind-turbine to the pump, the pump should possess, as near as possible, a quadratic power to speed ratio.

10.2 PERISTALTIC PUMP — COMMERCIALY AVAILABLE DESIGN

A relatively high torque is needed to start the "fixed inertia" pump, whereas the proposed self-regulating pump (see Figs. 35 and 36) would commence operating even in low speed winds. Under similar conditions a "fixed-inertia" pump would remain idle.

Because of its design simplicity and ease of operation, the peristaltic pump can be easily adapted to regulate a wind-driven peristaltic pump combination.

The major attribute of such a pump is that it has no mechanical drive into its pumping chamber, so the usually associated sealing problems are avoided. The pump (see Fig. 35) consists of a flexible tube, clipped to the curved track of the pump housing, concentric with which the drive unit rotates. As the large rollers of the drive unit pass over the tube, its contacted part becomes completely flattened, thereby driving forward the liquid in the tube. The simultaneous

WATER PUMPING

Commercially available design

relaxation of the tube behind the flattened portion sucks along further liquid which is subsequently displaced forward by the other roller compressing the tube. At any one time, at least one roller is pressed against the flexible tubing. A one-way valve, which is actuated by a very small pressure differential across it, ensures that reverse flow of the liquid does not occur.

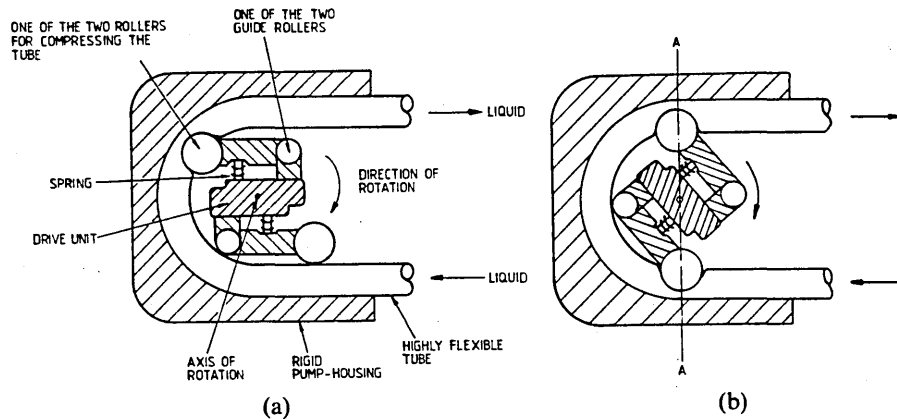


Fig. 35. Schematic representation of the commercially-available peristaltic pump: its components and operation. (a) Typical drive unit position, one roller compressing the tube. (b) Unique situation with both tapered rollers compressing the tube.

The drive unit is usually directly coupled to the wind-turbine shaft: this is easily achieved for both the horizontal and vertical-axis wind-turbines. But a pump fixed to the rotor axis may prove impractical for use with horizontal-axis rotors mounted on high towers. In such cases the pump would be situated at ground level with the appropriate coupling to the wind-turbine drive shaft.

10.2.1 Pump Operation

The pump is a modified version of a commercially-available unit (Ref. 133) and is shown schematically in Fig. 36. The two main alterations are;

1. tapered truncated-cone rollers replace the usual cylindrical ones, and
2. the drive unit is spring loaded.

WATER PUMPING

Commercially available design

The flexible tube is permanently held relative to the housing and the rotor and drive unit are fixed on the same shaft. The end of the drive unit is pressed against the spring on the support bracket.

At low wind speeds (and hence low rotational speeds) the "thin end" of the taper would press against the tubing. This would result in a relatively low compressive force being applied to the tube and hence a reduced load on the wind-turbine. Thus the rotor would start relatively easily, whilst pumping only small quantities of water.

At high rotational speeds the tubing would be pressed against the "wide end" of the truncated-cone rollers, so applying greater pressures to the tube. This would thus increase the retarding couple on the wind-turbine and so tend to reduce the rotational speed. The pump's normal, maximum efficiency, mode of operation will lie between these two extremes.

10.2.1.1 Horizontal-axis Wind-pump. -

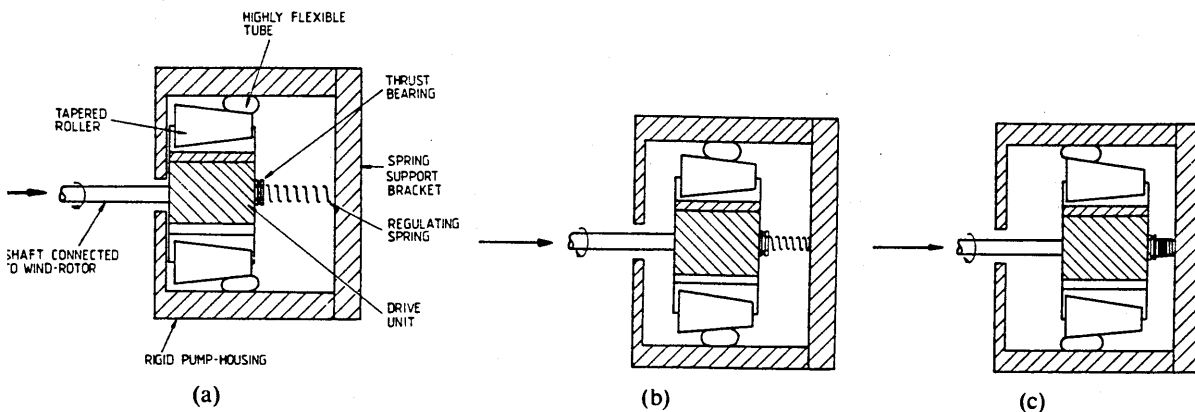


Fig. 36 Self-regulating peristaltic pump for the horizontal-axis wind-turbine: (a) starting mode; (b) normal operation; and (c) overspeed. For clarity, only the two rollers actually compressing the tube (in position AA of Fig. 35 (b)) are shown in the drawing.

As the wind speed increases, a greater couple is exerted on the horizontal-axis rotor — also on the shaft and drive unit — thereby squashing the spring (see Fig. 36). Then the wider portions of the tapered rollers are pressed against the tube, so displacing larger quantities of liquid.

WATER PUMPING

Commercially available design

10.2.1.2 Vertical-axis Wind-pump -

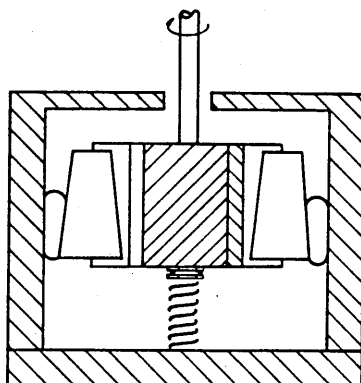


Fig. 37 Self-regulating peristaltic pump for the vertical-axis wind-turbine; again with both tapered rollers squashing the tube. (For part of the time, only one tapered roller is in contact with the flexible tube).

This design is identical to that of the horizontal-axis pump except that the tapered rollers are reversed (see Fig. 36). The pump is designed to be driven by the vertical-axis sail-type wind-turbine and self-regulation is achieved by the rotor being displaced upwards relative to the fixed tube in high speed winds. The sails of the wind-turbine would be designed so that the action of the wind "raises" the rotor slightly. This in turn, forces wider parts of the tapered rollers to be in contact with the flexible tubing.

10.2.1.3 Regulating Spring -

The spring is unnecessary for the operation of the pump because the tubing will always tend to force the rotor into its starting position. But the spring will be needed in order to regulate the wind-pump between the different operating positions, i.e. to dampen oscillations during wind gusts. It will also facilitate easier matching of the wind-turbine and pump.

10.2.2 Maintenance

The greatest concern when considering the use of a peristaltic pump is the worry of entrusting a liquid to an elastic tube which will be regularly flexed during the operation of the pump over several years. Within the pressures generated by the considered wind-turbines, this is not a severe problem, even though faster rates of deterioration of the flexible tube with tapered, rather than cylindrical, rollers occur. The maintenance programme should include the regular checking and replacement, if necessary, of both the regulating spring and the "working section" of the tube.

WATER PUMPING

"LOW-TECHNOLOGY" PERISTALTIC PUMP

10.3 "LOW-TECHNOLOGY" PERISTALTIC PUMP

Section 10.2 outlined the design and operation of a modified commercially-available peristaltic pump. The major disadvantage of it, is its initial capital cost. Such a peristaltic pump would be inappropriate for widespread use in Developing Countries unless it could be less-expensively manufactured there, using mostly traditional materials.

A more appropriate pump for such a situation would be a low-technology version of the peristaltic pump developed by Robertson and Leaman (Ref.134).

10.3.1 Pump Operation

The basic operating principles are the same as those of the previously described "commercially-available" peristaltic pump (see section 10.2.1).

The novel features of this design are;

1. the tube is externally wrapped around the drum and the roller compresses more than one revolution of the tube each revolution of the roller (see Fig. 38).
2. two sets of tubing are used in order to reduce the pump's starting torque. The outer tube is of a resilient material and the inner is a highly flexible tube.

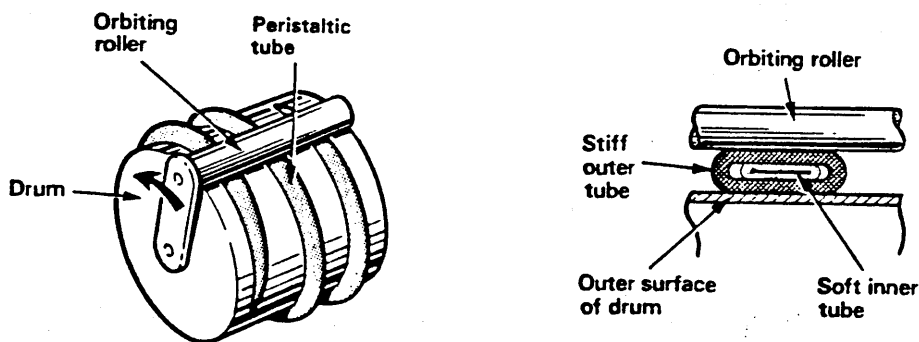


Fig. 38. Low-technology peristaltic pump

A single orbiting roller delivers fluid over the full (or nearly full) 360 degrees of rotation, with only one interruption per revolution, as the roller passes over the outlet end. This multiple-turn option results in several compression areas in the tube with the single roller giving a multiple seal effect, whilst still allowing the time of one revolution for the compressed area of the tube to regain its shape, and so draw in fresh fluid.

WATER PUMPING

Low-technology pump

For the double-tube system, the outer tube need only be compressed to the "flattened thickness" of the inner tube. This means that the outer tube is not distorted to the point of wall failure and enables the pump to operate at higher pressures since the inner tube can only expand to a limited extent before being constrained by the outer tube. This co-axial tube arrangement can also be used to improve the suction characteristics. By inter-connecting the inlet end of the inner tube and the space between the tubes, the pressure differential across the wall of the inner tube can be reduced to zero, thereby improving its recovery time before taking up further fluid.

The peristaltic pump can be driven in one of two ways:-

1. driving the central shaft, where the radial arm (see Fig. 38) is attached to the compression roller; or
2. driving the compression roller directly.

Because the roller is in contact with one area or another of the tube at all times, directly driving the roller becomes a practical proposition. This reduces the drag on the tubing as the roller winds itself around the drum, rather than being pushed over the tube surface. Tests (Ref.135) have shown that driving the roller directly gives far better performance than driving it indirectly.

10.3.2 Pump Construction

The pump (see Fig. 38), can be easily manufactured from readily-available discarded materials, thus overcoming the main problem associated with introducing "western techniques" into the Developing World (see Chapter 4).

Thus this pump, with its relatively low starting torque and cheap construction is ideally suited to be driven by a wind-turbine and to be used in developing countries.

CHAPTER 11

EXPERIMENTAL TEST FACILITY

The experimental test facility consisted of the wind tunnel with ancillary measuring instruments and wind-turbine support structures.

11.1 WIND TUNNEL

The wind tunnel had to accommodate the rotor and generate wind speeds up to 10 ms^{-1} . A 0.84 m diameter, 3.4 m long, open circuit duct (the air being directly exhausted, not recirculated) was used. This was capable of generating wind speeds of up to 20 ms^{-1} in the empty tunnel. Starting the fan was only possible when the starter motor was fully "wound down", giving a minimum dynamic pressure of 0.44 mm water gauge — this corresponded to a wind speed in the empty duct of 2.5 ms^{-1} .

The circular section wind tunnel (see Plate 2) of 0.84 m diameter was used in two different modes.

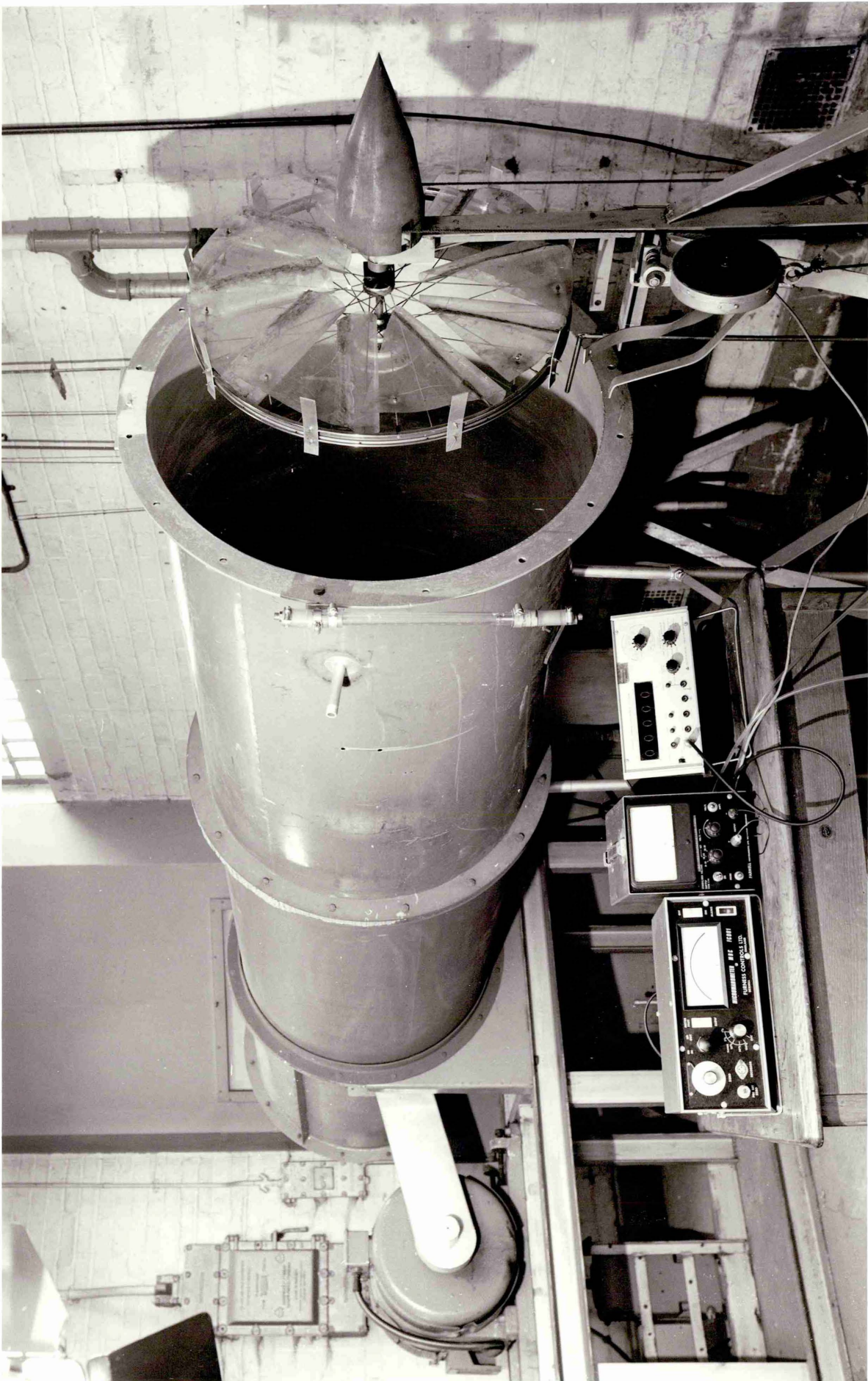
1. As a shroud for the rotor; the fan was employed in the "sucking mode" and the rotor was placed in the cylindrical shroud (wind tunnel) — see Fig. 23 — and,
2. Exhausting air directly onto the wind-turbine; the rotor and support stand were positioned at the duct exit as in plate 2.

Preliminary velocity traverses across the duct showed a non-uniform velocity distribution. Stroboscopic analysis highlighted an inconsistent fan speed, which was not improved by tightening the three belts driving the fan. On closer inspection, it was found that parts of some of the seven fan blades had been cut away, therefore accurate, uniform velocity profiles were impossible to attain. The velocity profiles are shown in Fig. 39.

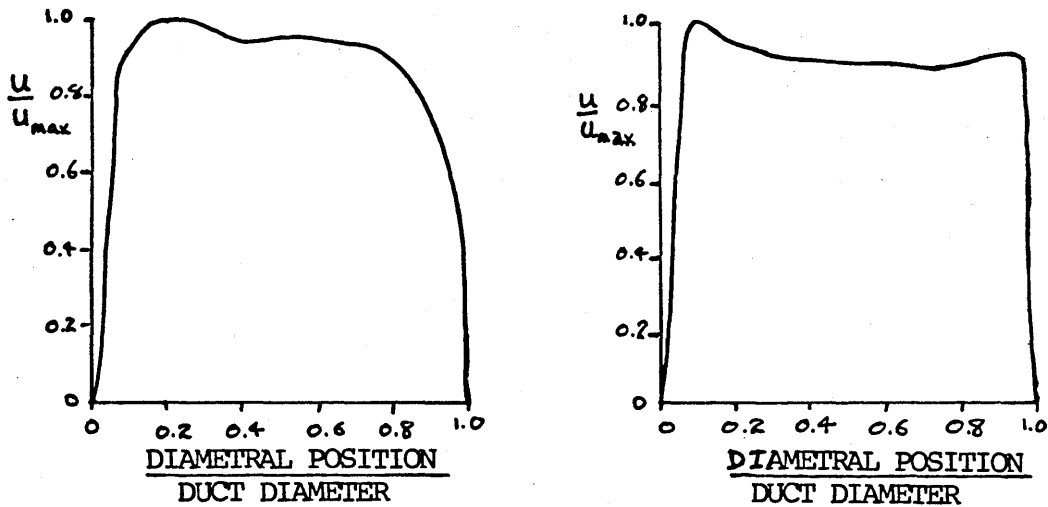
Fig. 39 (a) shows the initial velocity profile, whilst Fig. 39 (b) shows the profile after flow improvements were made.

Plate 2

Wind tunnel and ancillary measuring equipment with the horizontal-axis
test wind-turbine in situ.



TEST FACILITY
Wind tunnel



PRELIMINARY VELOCITY TRAVERSE ($u=5\text{ms}^{-1}$) VELOCITY TRAVERSE ($u=5\text{ms}^{-1}$) AFTER IMPROVEMENTS TO THE WIND TUNNEL

Fig. 39. Wind tunnel velocity profiles.

Construction of a more appropriate wind tunnel was investigated (see Appendix C), but the costs proved prohibitive, so the existing fan and duct-work were used.

11.1.1.1 Blockage Effects

Inaccuracies in the determination of the wind speed due to blockage are considered to have less an effect than the inconsistencies in the fan speed.

11.1.1.1.1 Horizontal-axis Test System -

The ratio of of the rotor diameter to the duct diameter was 0.76. This figure is unacceptably large for accurate quantitative readings.

11.1.1.1.2 Vertical-axis Test System -

Since the Savonius wind-turbine rotates around the vertical-axis, the resultant wake experiences large cross-wind forces as well as moderate "wind-wise" forces. Thus Savonius rotors require a much larger ratio of tunnel area to rotor area for adequate quantitative study. The ratio of the Savonius turbine to the duct cross-sectional area was 0.60.

Accordingly the data presented in Chapter 12 should be treated as comparative and not absolute.

TEST FACILITY
Wind tunnel

11.1.2 The Fan

This was an R.R. Briton, of Shepton Mallet, reconditioned variable speed motor-driven fan. Some of the fan blades had sections cut out of them, probably to balance the fan prior to previous research. The side elevation of the fan is shown, along with the fan after-body, in Fig. 40.

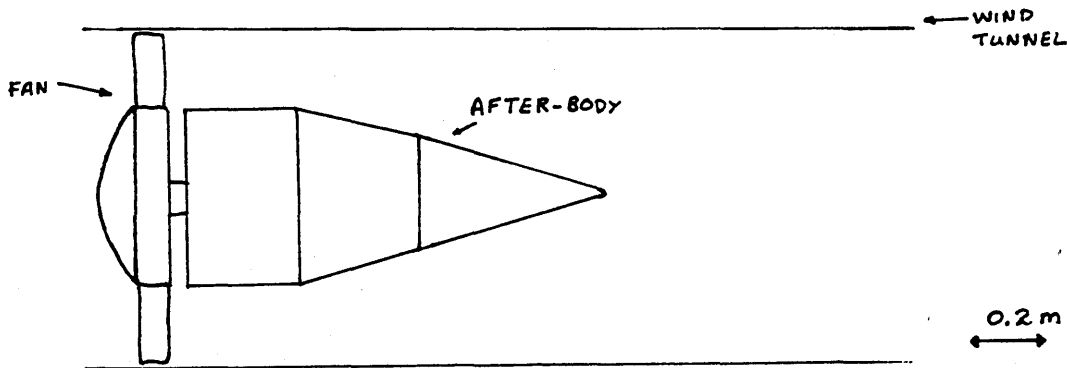


Fig. 40. Wind tunnel fan and fan after-body.

11.1.3 The After-body

In order to "smooth" the air flow from the fan, a large after-body was constructed. The after-body (see Fig. 40) was placed immediately behind the fan. This reduced the fluctuations in measured air velocity but unfortunately was unable to eliminate them completely.

11.2 WIND-TURBINE SUPPORT STRUCTURES

11.2.1 Horizontal-axis

11.2.1.1 Shrouded Test Sequence -

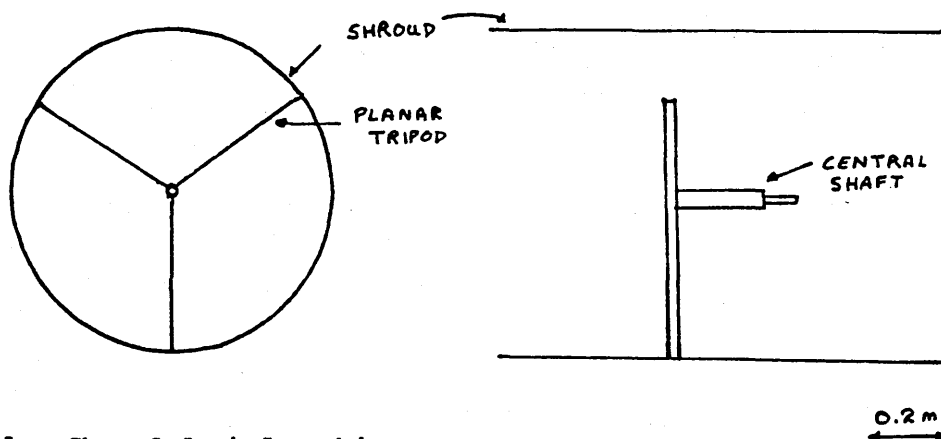


Fig. 41. Shrouded wind-turbine support structure.

TEST FACILITY
Support structures

This wind-turbine support had to fit into the wind tunnel duct and hold the plane of the rotor centrally at right-angles to the air flow (see Fig. 41). It consisted of a planer tripod arrangement welded to a central shaft on which the rotor and bearings rotated. The loose (standard cycle wheel) bearings were held in place by the bearing nut and the hub of the wheel (see Fig. 42) and allowed the rotor to rotate on the fixed, stationary shaft.

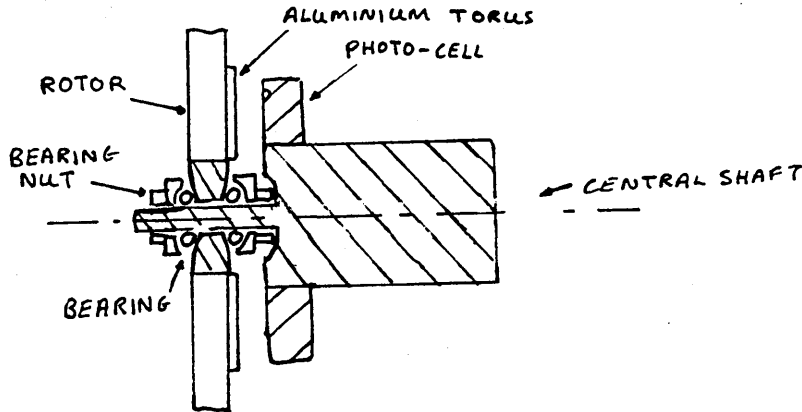


Fig. 42. Shrouded wind-turbine bearing housing and speed measuring equipment.

11.2.1.2 Unshrouded Test Sequence -

As the shrouded wind-turbine central shaft was held stationary, it was unable to drive a pump directly through that shaft. Accordingly, the bearing assembly was re-designed for the unshrouded wind-turbine, to enable the shaft to rotate with the rotor and so drive the pump. The wind-turbine central shaft was located in the bearing housing (see Fig. 43) by means of circlips. The rotor was then simply held on to the shaft by the appropriate nuts. This also facilitated the removal of the wind-turbine in order to vary the different parameters, the effects of which were to be tested.

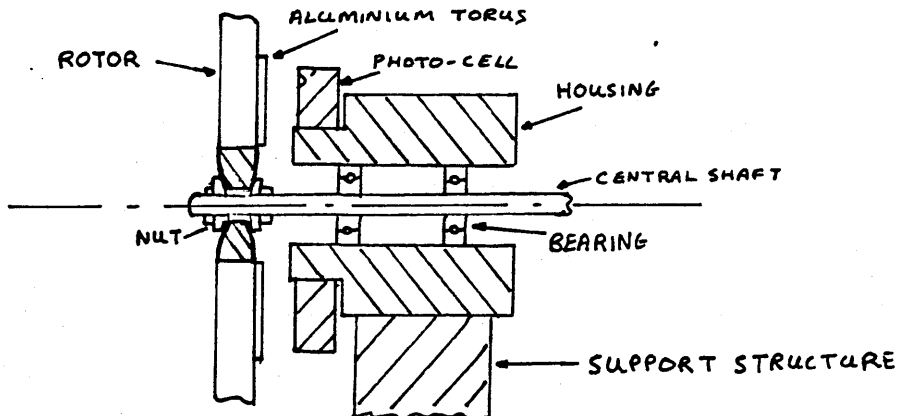
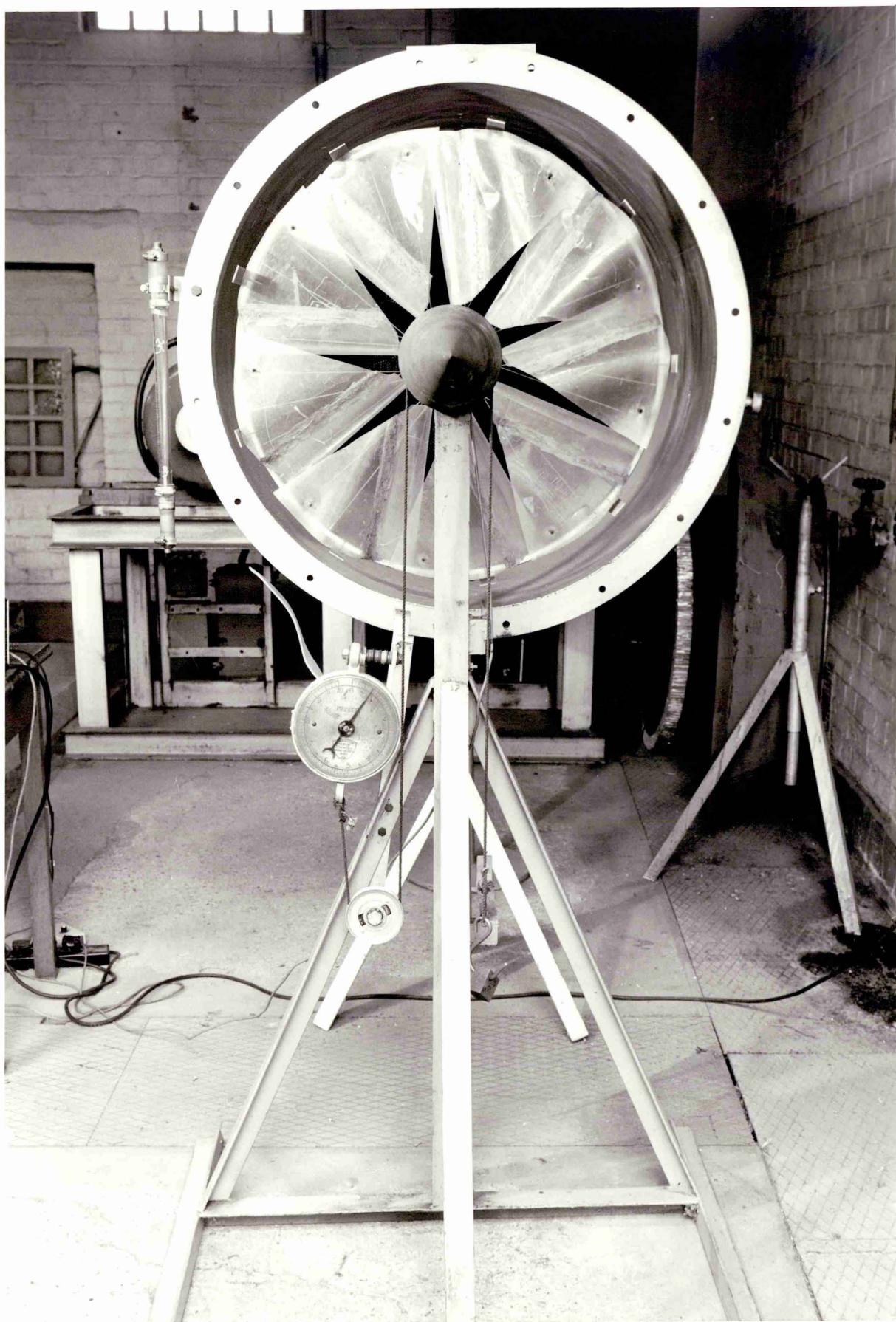


Fig. 43. Unshrouded wind-turbine bearing housing and speed measurement.

Plate 3

Horizontal-axis wind-turbine support structure.



TEST FACILITY
Support structures

The free-air rotor support structure (see Plate 3) held the wind-turbine orthogonol to the wind tunnel axis and incorporated the spring balance assembly for the torque measurement. An attachment to enable stationary hub-fairings to be tested, was bolted to the framework, when required.

11.2.2 Vertical-axis

The vertical-axis rotor had to be supported so that,

1. its centre was perpendicular to the tunnel axis,
2. the airflow above and below the two plates was largely uninterrupted, and
3. it could be easily dismantled.

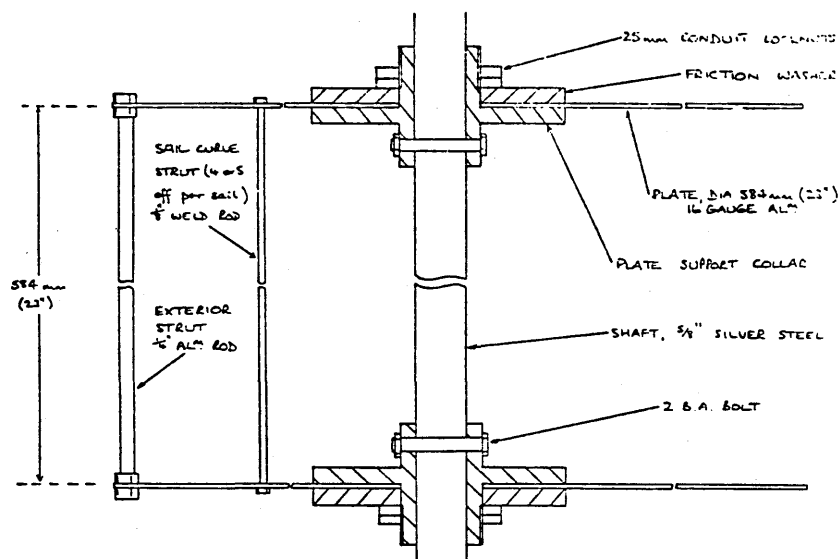
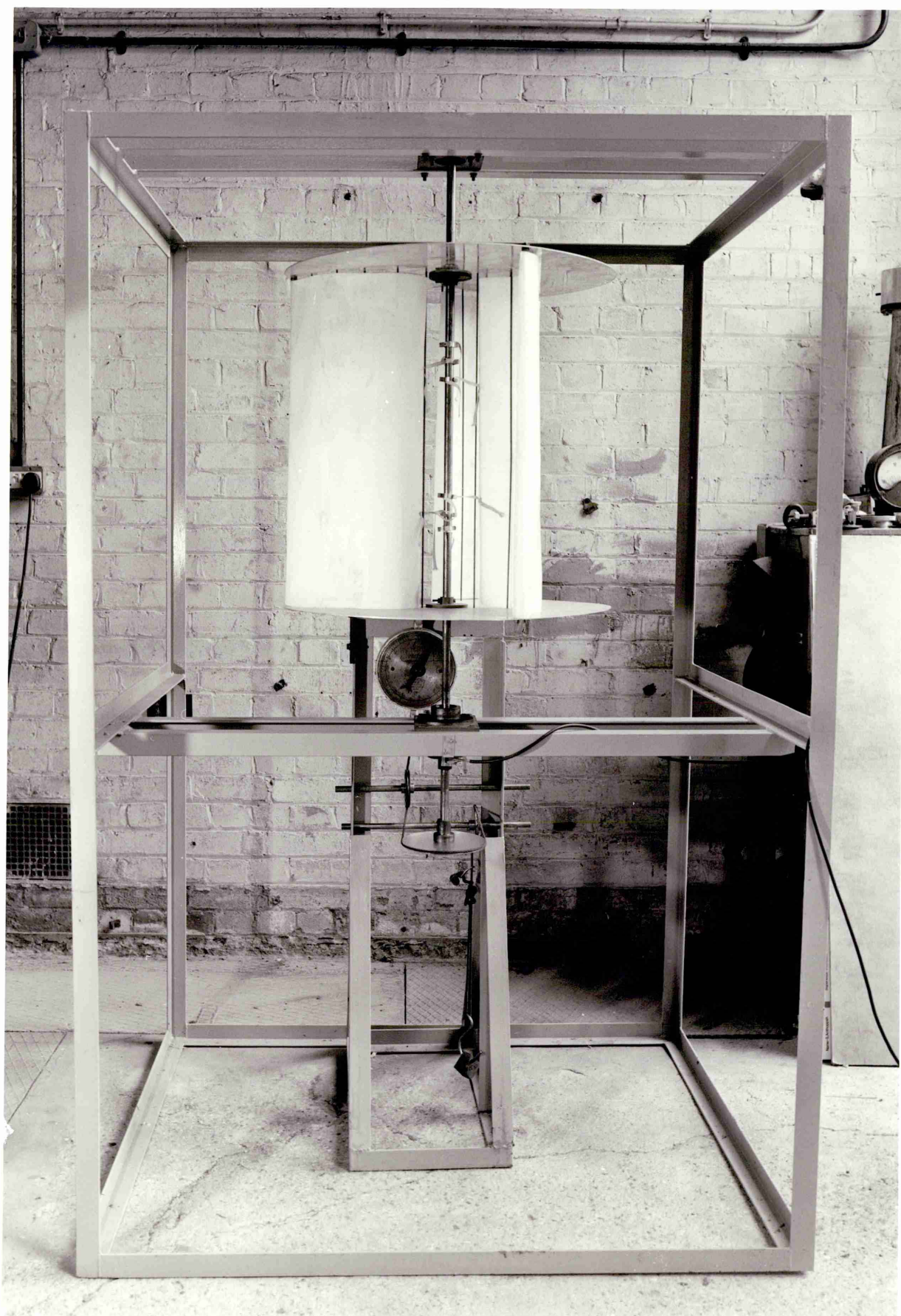


Fig. 44. Vertical-axis wind-turbine constructional details.

A simple rectangular frame of dimensions 1.85 m by 1.22 m by 1.02 m was constructed from 0.044 m steel angle iron. The rotor shaft was supported at 0.305 m from the edge of the leading plane of the frame, on two pairs of horizontal cross-members (see Plate 4) each of which supported a bearing assembly (see Fig. 44) and left 0.02 m of "free wind" either side of the rotor plates. The rotor was suspended from the upper bearing by means of a collar (see Fig. 45), the lower bearing providing no axial thrust. To avoid assembly stress in the shaft, the bolt clearance holes of the bearing assemblies were drilled over-size. Thus on assembly, the upper bearing was locked in position, whilst the lower was allowed to find its own suspended position before being locked itself.

Plate 4

Vertical-axis wind-turbine support structure.



TEST FACILITY
Support structures

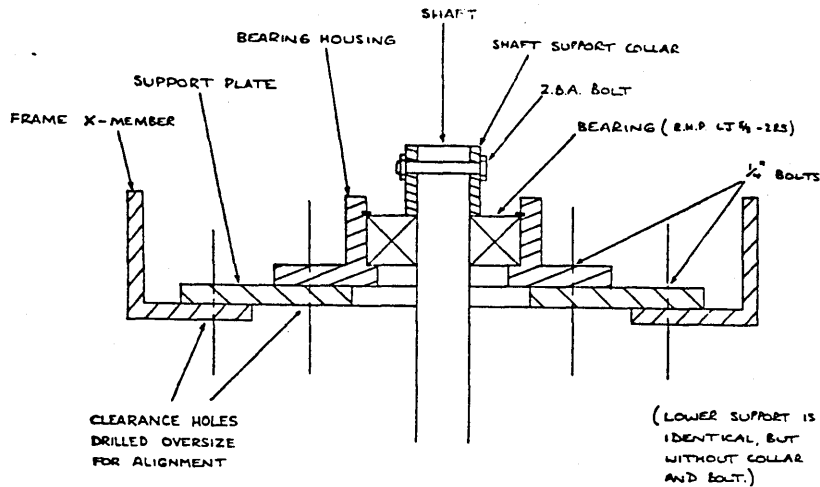


Fig. 45. Vertical-axis wind-turbine upper support shaft assembly.

Because the rotor had to be easy to dismantle (i.e. for drilling the plates to test a different sail profile), the lower bearing was a tight fit on the shaft whilst the upper one was able to slide off easily — the diameter at the top end of the shaft was slightly reduced.

The dismantling procedure was as follows:-

1. remove the pulley and photo-cell assembly,
2. remove the sails and support rods,
3. remove the bolt of the upper plate and slide the upper plate down to rest on the lower plate,
4. jerk the shaft upwards to lift the bearings clear of the bearing housing,
5. remove the upper bearing from the shaft, and
6. remove the shaft and the plates.

Finally, the front of the frame was bolted to the tunnel and the side of the frame to the test-house wall, resulting in the elimination of excessive vibration.

11.3 TORQUE MEASUREMENT

Three different types of torque measuring devices were considered;

1. a water dynamometer,
2. an electrical dynamometer, and
3. a friction dynamometer.

TEST FACILITY
Torque measurement

A small water brake would have been capable of damping any torque fluctuations. These devices are widely used for measuring relatively large torques (i.e. in engine testing), but a suitable design on the scale required here would have been difficult to realise. Accordingly this method was not considered feasible.

Electrical dynamometers are commercially available and are arguably the preferred choice. However the cost of the accompanying amplification and display equipment was prohibitively expensive.

A simple friction brake was thus used throughout.

11.3.1 Horizontal-axis

The torque was measured via the brake dynamometer, using both weights and a spring balance for stability. This simple type of brake consisted of a rope (of radius r_2) passing round a pulley (radius r_1) securely attached to the rotor hub. The rope made a half turn round the rotor pulley then another half turn round the guide pulley as shown in Plate 1. Fig. 46 shows, schematically, the torque meter arrangement.

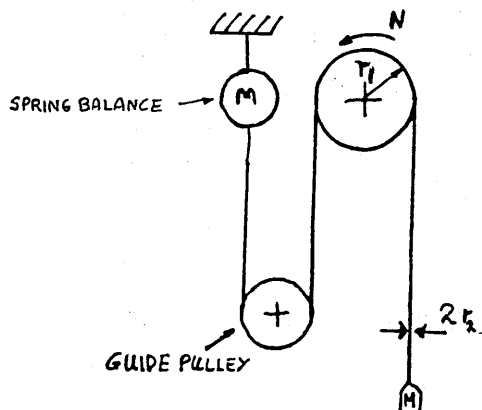


Fig. 46. Horizontal-axis wind-turbine torque measurement arrangement.

Tension was produced in the rope, due to the weight (i.e. Mg) of the mass M at one end, and at the other, by the pull (mg) of the spring balance m .

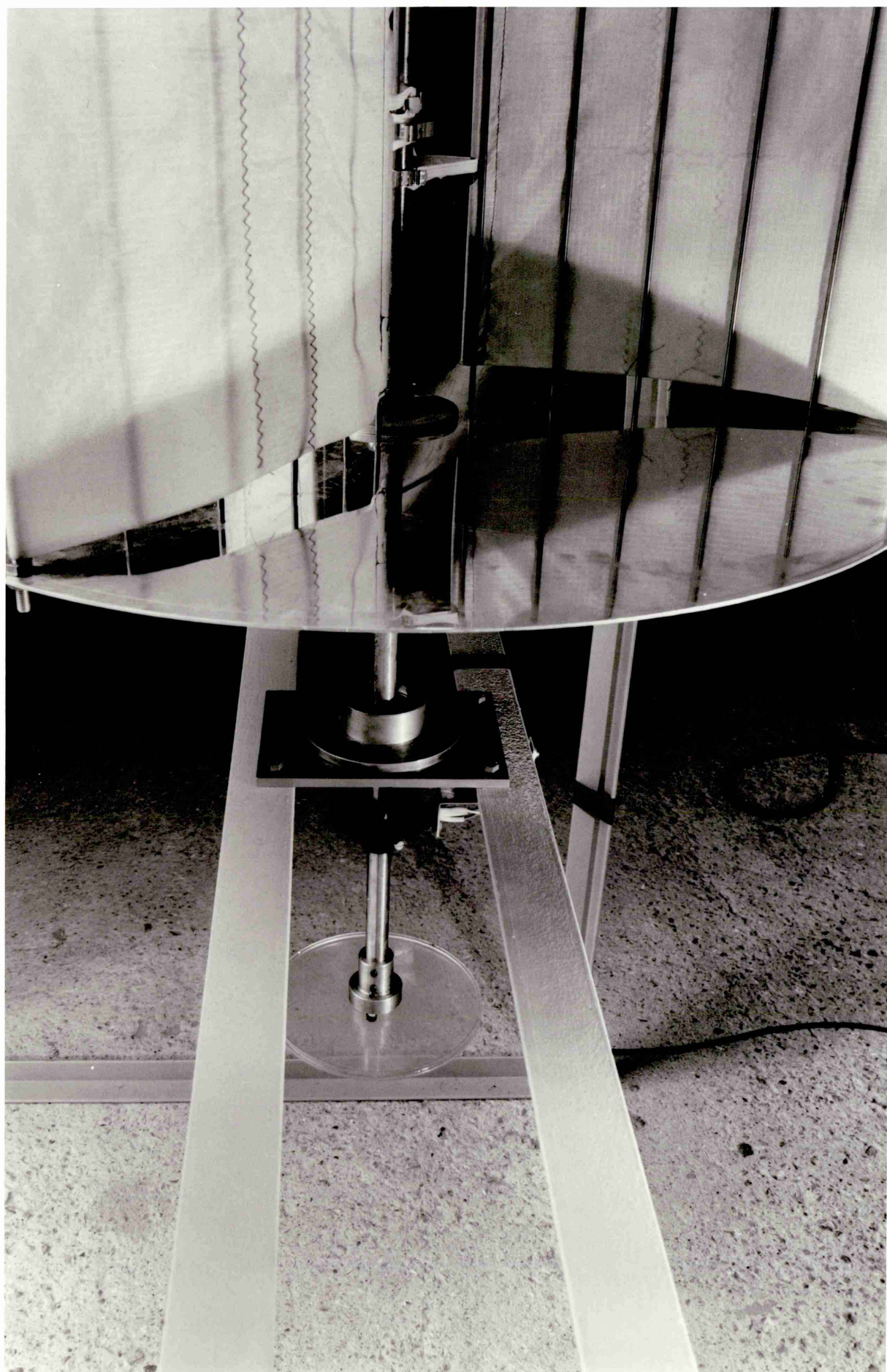
The torque Q applied by the rope brake is thus given by ;

$$Q = (M-m) (r_1 + r_2) g \quad (98)$$

Various types of rope were tried, including braided nylon and leather, but these gave constant readings at different wind speeds or excessive oscillations of the mass M . These problems were overcome by using well-oiled cotton "tent" rope.

Plate 5

Vertical-axis wind-turbine — central shaft, lower support plate
and bearing assembly.



TEST FACILITY
Torque measurement

11.3.2 Vertical-axis

A Perspex pulley (152 mm in diameter) was attached to the lower end of the shaft (see Plate 5), its circumferential groove located the cotton "tent" rope. The rope's tension could be simply varied and so apply a torque to the rotor. By means of two axles and brass wheels mounted in a separate frame, weights could be applied to one end of the rope, whose other end was connected to the spring balance (this is shown in Plate 3). The difference between the tensions in the rope on either side of the pulley indicated the torque applied to the rotor.

In an effort to reduce the effect of friction losses (and hence errors in the torque measurement) between the brass tensioning wheels and their respective axes, the wheel bores were reamed and oiled. Their circumferential rope grooves were set at a radius of 32 mm from the axle centre-lines. In fact the slightly variable nature of the torque maintained these wheels in almost constant to-and-fro motion on their axles: this ensured that a true mean torque was indicated, as static friction was continually being overcome and reversed.

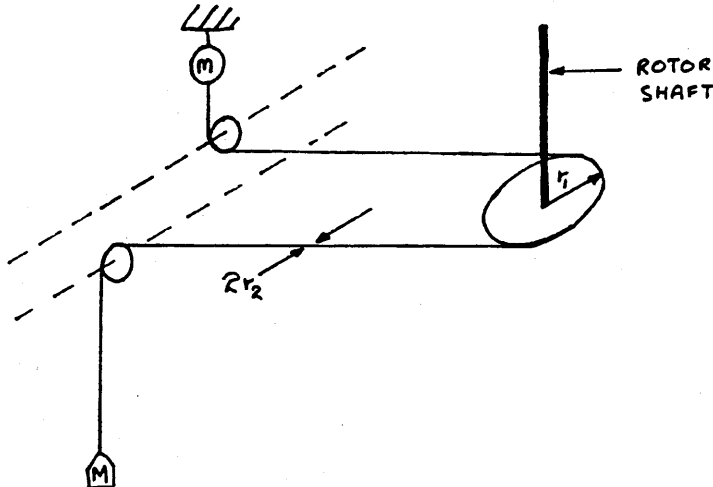


Fig. 47. Vertical-axis wind-turbine torque measurement arrangement.

The vertical-axis torque meter is shown schematically in Fig. 47. If the balance reading is m and the weight applied is M , then the torque applied to the wind-turbine is given by,

$$Q = (M-m)(r_1 + r_2)g \quad (99)$$

where r_1 is the pulley radius and r_2 is the radius of the rope.

11.4 ROTOR SPEED MEASUREMENT

The rotor speed was determined by integrating the number of revolutions of the rotor over 10 seconds. A photo-cell unit was placed on the rotor shaft approximately 6 mm from the reflective, planar aluminum torus attached to the rotor hub. The torus for the horizontal-axis wind-turbine had 6 light and 6 dark segments (see Plate 1) whilst for the vertical-axis, the torus had 6 radial sections

TEST FACILITY

Rotor speed measurement

cut out of it (see Plate 5). A continuous light-beam, fed from the 5 V stabilised voltage supply, was reflected on (or through, for the vertical-axis wind-turbine) the respective torus. The pulses of reflected light were sensed by the photo-cell and the impulses relayed to the electronic counter. The counter recorded the pulses over a period of 10 seconds, thereby displaying the rotor speed in revolutions per minute.

11.5 WIND SPEED MEASUREMENT

The wind speed was measured directly in front of the rotor, using a pitot-static tube and a micro-manometer (see Plate 1). The manometer reading corresponded to the dynamic head ($\frac{1}{2}\rho u^2$) from which the wind speed was readily determined as the density of the air is known. The micro-manometer was "zeroed" on the "one per cent" scale, thereby achieving the greatest accuracy. There was no danger of the manometer being over-loaded as the fan would only start at a dynamic pressure of 0.44 mm of water (corresponding to a wind speed of approximately 2.5 ms^{-1}). A standard pitot-static tube was used, no correction being made for swirl, as the inaccuracy was considered negligible.

11.6 WIND-TURBINE POWER OUTPUTS

The wind-turbine power outputs were able to be determined via one of two methods.

11.6.1 The Product Of Torque And Rotor Speed

From Chapter 5, section 5.2.4, the power harnessed by the wind-turbine is the product of its developed torque and the rotor's rotational speed (measured in radians per second). Thus the wind-turbine's power outputs were simply determined by recording the torque (at a particular rotational speed) and multiplying this by the rotor's rotational speed.

11.6.2 Hydraulic Power

The facility also existed to record the wind-turbine power output whilst driving a positive-displacement pump. The pump (see Chapter 10) was coupled to the central shaft of the wind-turbine, with its inlet and outlet pipes a fixed distance (h) apart. A flow-meter was present in the circuit (see Fig. 48).

TEST FACILITY
Wind-turbine power outputs

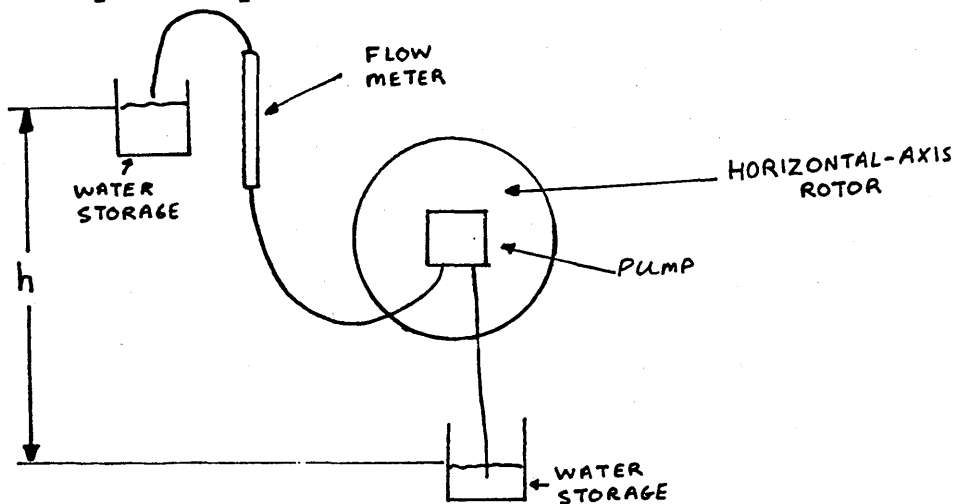


Fig. 48. Schematic representaiton of the hydraulic power measurement equipment.

The power required to drive the pump is given by;

$$\text{Useful work done by the pump} = \dot{V} \rho g h \quad (100)$$

11.7 EXPERIMENTAL PROCEDURE

The test sequence was common for both types of wind-turbines tested.

1. Switch on the power supply to the recording instruments and allow fifteen minutes for them to "warm up".
2. Place the appropriate wind-turbine in front of the tunnel.
3. Ensure that the aluminium torus is facing the photo-cell with a gap of about 6 mm.
4. After the "warm up period" has elapsed, zero the micro-manometer and electronic counter, after ensuring that the stabilised voltage supply is delivering 5 V.
5. Loop the rope round the appropriate pulleys
6. Switch on the fan motor. This is only possible when the motor is fully "wound down". Set the required dynamic pressure to obtain the desired wind speed.
7. Record the following; spring balance reading (m), mass (M), rotor speed (N) and the wind speed (u).
8. Repeat for other wind-turbine configurations as required.

CHAPTER 12

ANALYSIS OF EXPERIMENTAL DATA

12.1 INTRODUCTION

Problems of test accuracy arose because of the limitations of the wind tunnel (see Chapter 11, section 11.1). The small diameter of the duct relative to the rotor resulted in considerable blockage and the inconsistent fan speed gave slight fluctuations in the velocity profiles (see Fig. 39).

The data presented in this chapter should thus be regarded as comparative and not absolute.

12.2 WIND SPEED

A wind speed of 5 ms^{-1} was adopted as this was considered a representative speed. It roughly corresponds to the median wind speed in the United Kingdom (Ref. 136) and is a typical wind speed in many rural areas of developing countries.

The shrouded wind-turbine data were obtained in a wind speed of 5 ms^{-1} inside the shroud — this in fact corresponded to a slightly lower "free wind speed" (i.e. the undisturbed wind speed outside the wind-tunnel). The "free wind speed" was unable to be recorded as the wind tunnel was used in the "sucking mode" i.e. drawing air into the duct, so only enabling the the wind speed to be recorded inside the duct. The subsequent tests (i.e. the unshrouded wind-turbine data) were conducted in a wind speed approximately equal to 5 ms^{-1} . Due to slight differences in measuring the wind speed, that recorded for the tip-fin augmented wind-turbine was approximately 0.4 ms^{-1} higher than for the centre-body and the tip-fin plus centre-body augmented wind-turbine tests. This is further discussed in section 12.3.3.

EXPERIMENTAL DATA
HORIZONTAL-AXIS WIND-TURBINE

12.3 HORIZONTAL-AXIS WIND-TURBINE

12.3.1 Shrouded Wind-turbine Measurements

Two types of sail configuration were tested;

1. The "rim-attached" arrangement, i.e. a "Cretan-type" sail system adapted to suit the limitations of using the cycle wheel. Each sail was fixed to the wheel rim, with the sail angle adjustment at the leading edge.
2. The "sail-with-pole" arrangement, i.e. a loosely sheeted sail with the leading edge wrapped around the spoke and fastened to itself, the sail angle adjustment being at the trailing edge of the sail.

The advantage of the latter sail type was its ability to be shaped by the wind. This gave a simple way of obtaining an aerofoil profile. The various test systems are shown in Table 3.

Table 3.
Shrouded wind-turbine test systems —
nine individual sails on the 0.64 m diameter rotor.
The sails were made of Melinex, 0.125 mm thick.

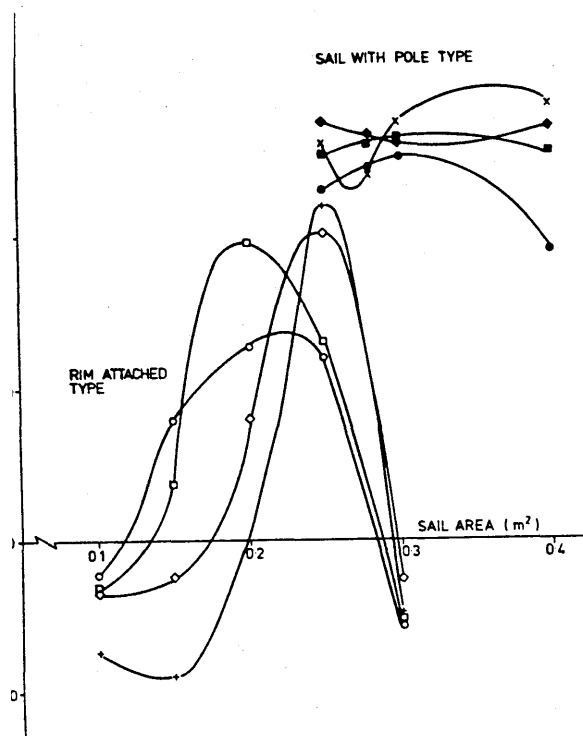
Test system	Individual sail area (10^{-1} m^2)	Solidity ratio	Configuration
A1	0.10	0.28	ras
A2	0.15	0.42	ras
A3	0.20	0.56	ras
A4	0.25	0.70	ras
A5	0.30	0.81	ras
A6	0.25	0.70	swp
A7	0.28	0.78	swp
A8	0.30	0.84	swp
A9	0.40	0.95	swp

ras = Rim attached sail.
swp = Sail with pole.

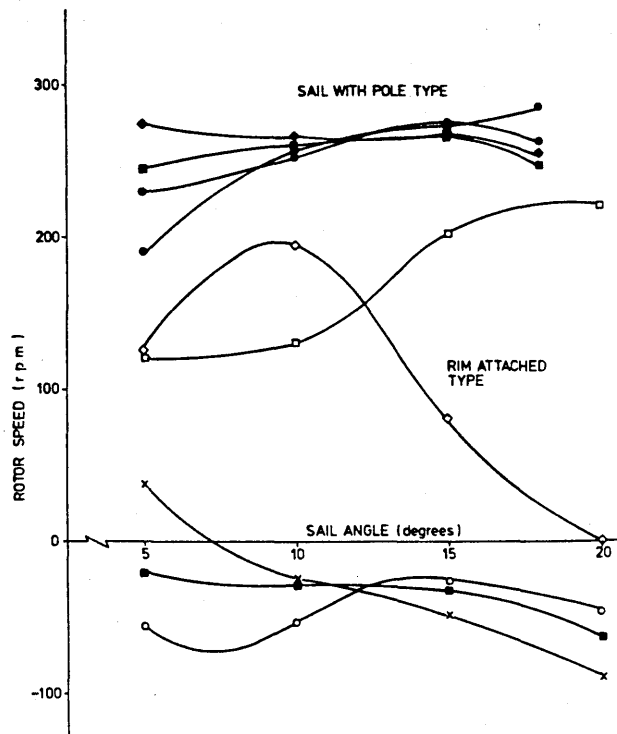
The tests undertaken involved varying:

1. the type of sail configuration,
2. the solidity ratio, by changing the sail area and
3. the incidence of the sail, which is subsequently referred to as its "angle".

The solidity ratio, defined as the ratio of the sail area to the area swept by the sails, is determined by the projection of the sails on the plane of rotation. The sail angle is the angle that an imaginary flat sail makes with the plane of rotation, when its trailing edge is displaced axially as far as the sail attachment clamp allows.



angle ees)	Rim attached sail type	Sail with pole type
	○	●
	□	■
	◇	◆
	+	×



Individual sail area (10 ⁻¹ m ²)	Rim attached sail type Test system	Symbol	Solidity	Sail with pole type Test system	Symbol	Solidity
0.10	A1	⊠	0.28			
0.15	A2	×	0.42			
0.20	A3	◇	0.56			
0.25	A4	□	0.70	A6	●	0.70
0.28				A7	■	0.78
0.30	A5	○	0.81	A8	◆	0.84
0.40				A9	⊗	0.95

Fig. 49. Comparison of the wind-turbine performance using either rim-attached sails or sail-with-pole configuration: sail area against maximum rotational speed.

Fig. 50. Comparison of the wind-turbine performance using either rim-attached sails or sail-with-pole configuration: sail angle against maximum rotational speed.

The early results (see Figs. 49 and 50) are for "free rotor" tests; that is without the torque meter operating. The "rim-attached-sails" harnessed very little power (less than 1 W maximum in a 5 ms⁻¹ wind speed), so torque and power characteristics are only presented for the "sail-with-pole" type attachments (see Figs. 51 to 60). Because of its superior power-harnessing characteristics, this is the configuration that is recommended for practical use.

The tendency for the "rim-attached-sails" to rotate in the reverse direction (see the lower curves of Figs. 49 and 50) was another disadvantage and partly due to their intrinsic tightness and consequent inability to be shaped by the oncoming wind. This reversal embarrassment was avoided with the "sail-with-pole" configuration, as the wind easily fashioned the loose sails, giving relatively high starting torques and so affirming that the wind-turbine would always drive the pump in the required direction. Due to the presence of the shroud and the small, light-weight rotor, maximum power extraction is achieved at relatively high rotor speeds compared with other, larger, sail-type wind-turbines.

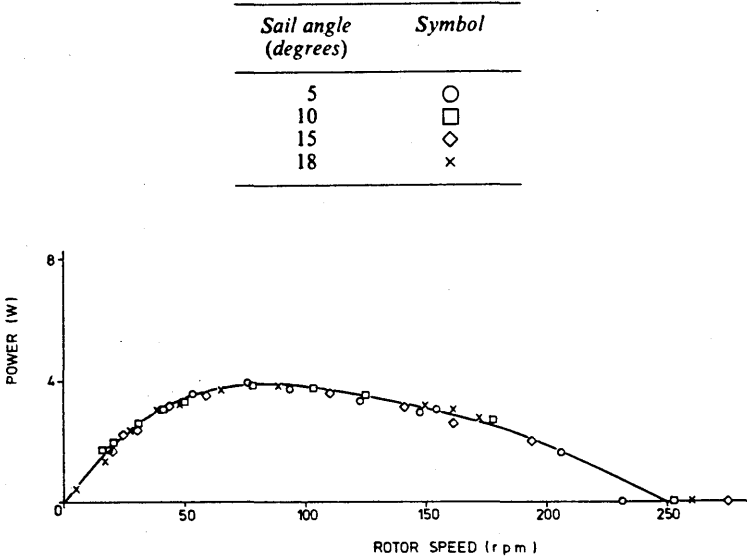


Fig. 51. The effect of sail angle on the power characteristics of the wind-turbine with test system A6.

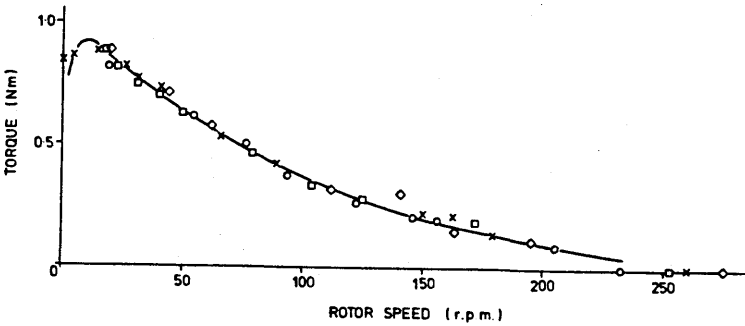


Fig. 52. The effect of sail angle on the torque characteristics of the wind-turbine with test system A6

EXPERIMENTAL DATA
Horizontal-axis — shroud

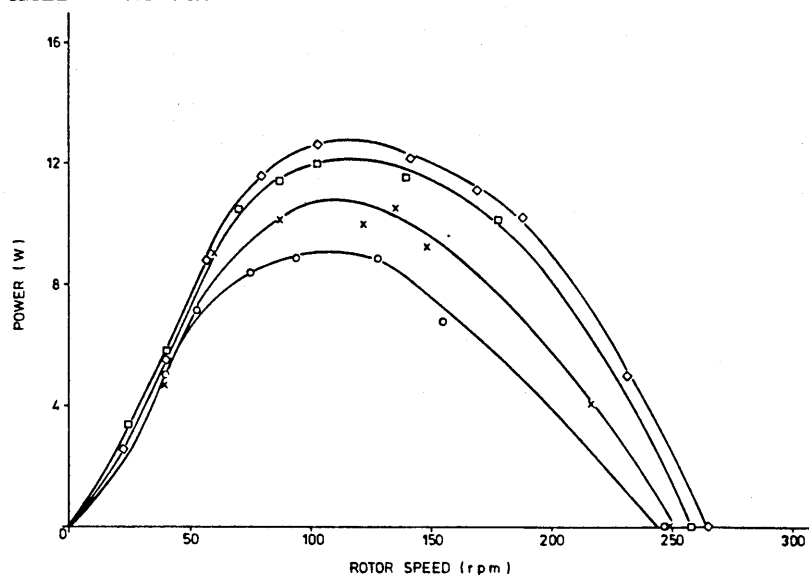


Fig. 53. The effect of sail angle on the power characteristics of the wind-turbine with test system A7.

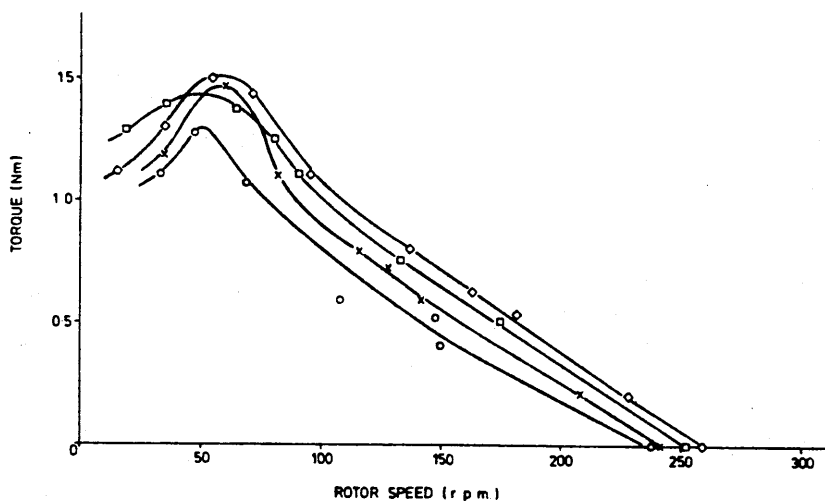


Fig. 54. The effect of sail angle on the torque characteristics of the wind-turbine with test system A7.

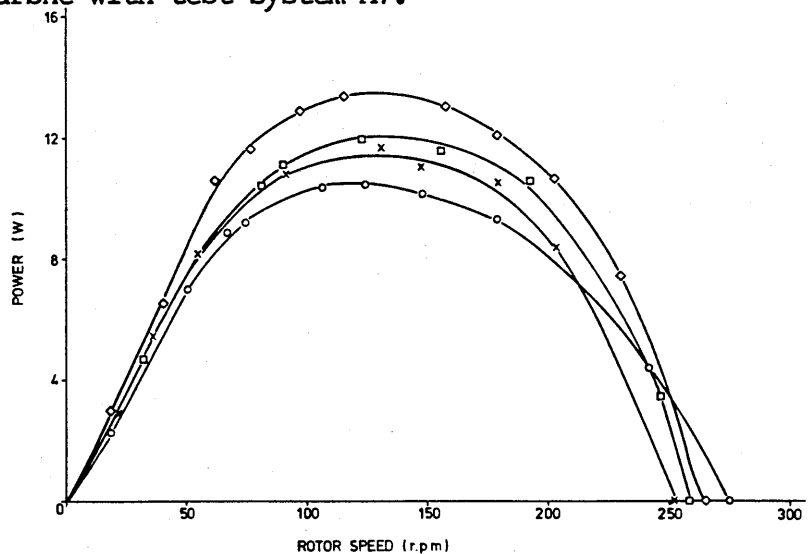


Fig. 55. The effect of sail angle on the power characteristics of the wind-turbine with test system A8.

EXPERIMENTAL DATA
Horizontal-axis — shroud

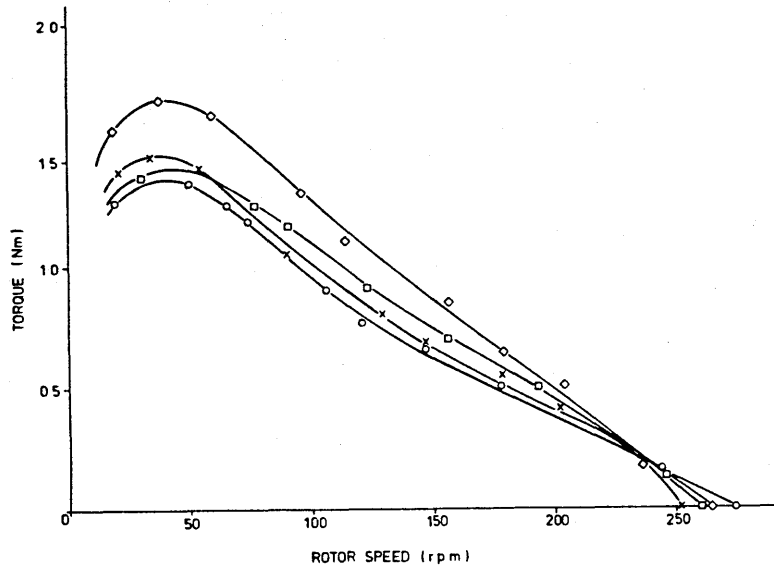


Fig. 56. The effect of sail angle on the torque characteristics of the wind-turbine with test system A8.

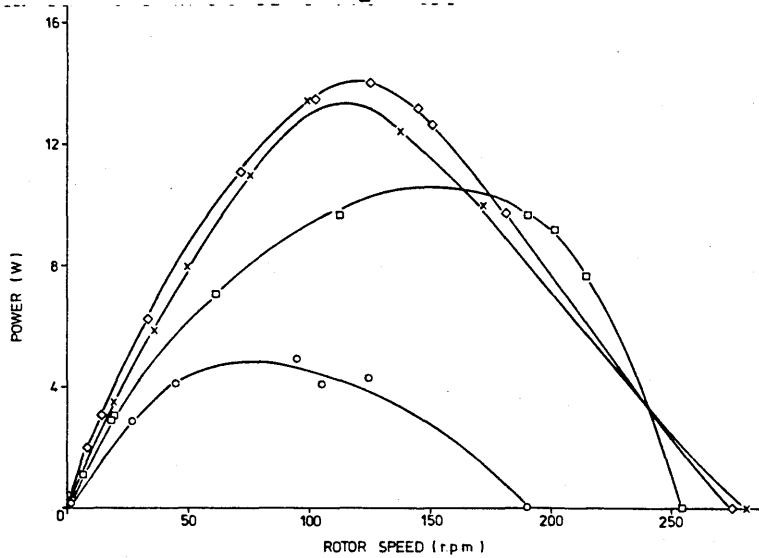


Fig. 57. The effect of sail angle on the power characteristics of the wind-turbine with test system A9.

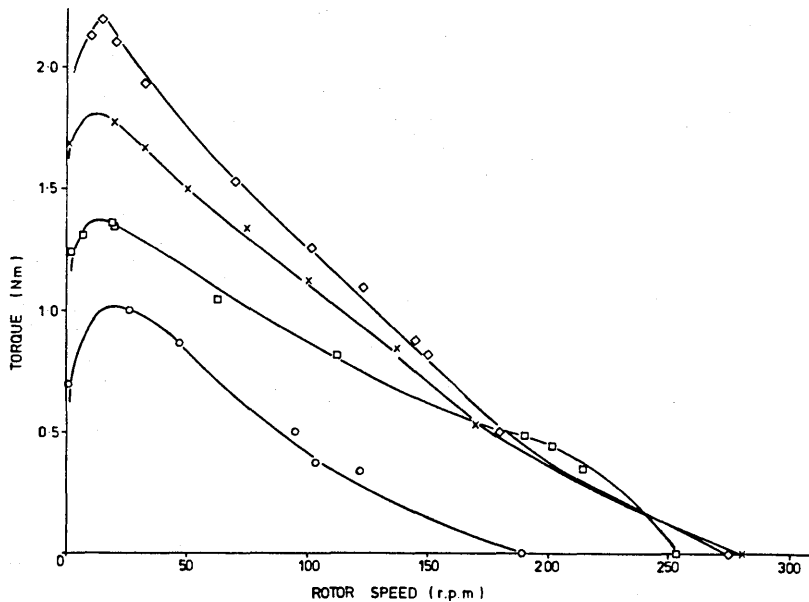


Fig. 58. The effect of sail angle on the torque characteristics of the wind-turbine with test system A9

EXPERIMENTAL DATA

Horizontal-axis — shroud

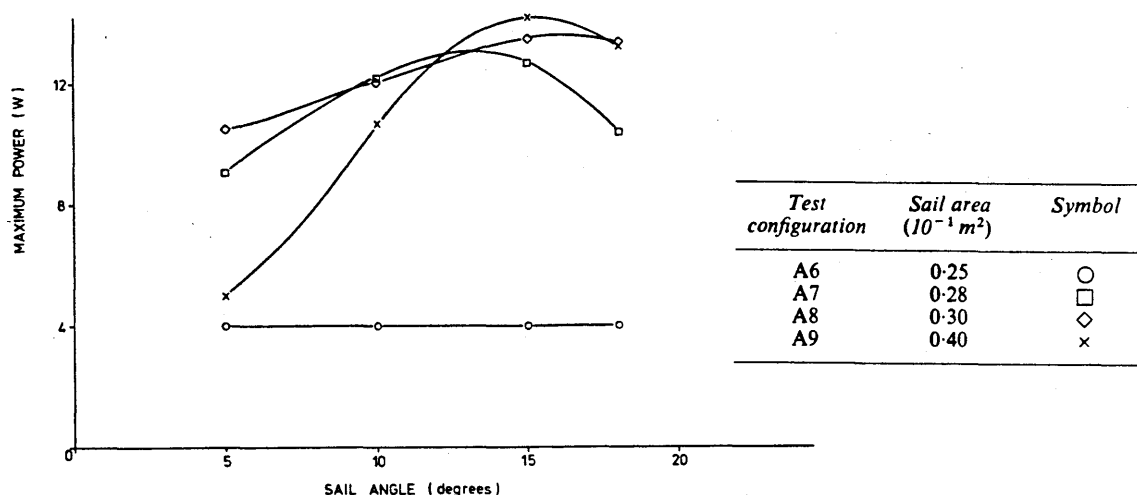


Fig. 59. The effect of sail angle on the maximum power harnessed by the wind-turbine with test systems A6, A7, A8 and A9.

From Figs. 51 to 59, it is apparent that the maximum values of the torque and harnessed power, for the shrouded wind-turbines occur at different rotational speeds. This is because power is the product of torque and rotor speed (measured in radians per second). Therefore, at rotor speeds greater than 70 r.p.m., the variation in speed is more dominant than the variation in torque. Maximum power, therefore, is obtained at a higher rotor speed than that at which maximum torque occurs.

Experimental data (see Figs. 51 and 52) showed that, for the test system A6, the torque developed and power extracted were both independent of sail angle.

The "sail-with-pole" test system A7 (see Figs. 53 and 54) developed a high torque at low rotor speeds, with the maximum torque occurring at 60 r.p.m. The maximum power was 9 W and 10.5 W for 5 and 20 degree sail angles respectively, but the greatest maximum power of 13 W ensued for a sail angle of 15 degrees at a rotor speed of 115 r.p.m. For test system A8 (see Figs. 55 and 56), the maximum torque occurred at approximately 40 r.p.m. for all sail angles. Again maximum power was achieved with a 15 degree sail angle but at a slightly greater rotational speed (125 r.p.m.).

For test system A9 (see Figs. 57, 58 and 59) the maximum power — over three times that for A6 — was harnessed at an angle of 15 degrees. This was due to the large loose sails used (a solidity of 95 per cent). A slight overlap of the sails was evident in still air: this is shown by the performance characteristics of A9 at angles of 5 and 10 degrees. At an angle of 5 degrees, the performance is relatively poor due to the small displacement of the sail from the spokes, resulting in the sails still slightly overlapping. For a 10 degree sail angle configuration, the larger sails resulted in the maximum power being extracted at a higher rotor speed, so tending to increase the torque developed at about 200 r.p.m. Maximum torque (see Fig. 57) was developed at a lower rotor speed (120 r.p.m.), so tending to facilitate starting in lower speed winds.

EXPERIMENTAL DATA Horizontal-axis — shroud

At its maximum power, sail A9 gave an augmentation factor of about unity (i.e. a maximum power coefficient of approximately 0.59) relative to the wind speed u , at the rotor (i.e. inside the shroud). This is due to the reduced tip losses as the air flow is constrained within the shroud. The augmentation factor would be considerably larger, when based upon the correspondingly lower free wind speed U .

The shroud is a large and expensive addition to the cheap, flexible sail wind-turbine tested here. Attaching tip-fins to the rotor rim could theoretically increase the power output of the unshrouded wind-turbine (see Chapter 7, section 7.2.2) more cost-effectively.

Accordingly the tip-fins (and centre-body) augmented wind-turbine tests were performed outside the duct — i.e. in the "free-air" (see Chapter 11 section 11.2.1.2).

12.3.2 Tip-fin Augmented Wind-turbine Measurements

The first series of tests on the augmented wind-turbine permitted the determination of the optimal number and recommended position of the tip-fins. The cycle wheel facilitated fins being attached to the rim and the effects of three, six and nine tip-fins being tested in each of the three positions — these are shown in Fig. 60 (a). Position I was where the sail displacement — the horizontal distance between the rim and the considered zone of the sail — was anticipated to be greatest (and conventionally referred to as the sail pitch), see Fig. 60 (b). Position II corresponded with the rim anchorage point for the next adjacent wheel spoke, where the sail displacement was less, whereas position III which was near the sail trailing edge (appropriate to the next spoke anchorage point) corresponded to a small sail displacement.

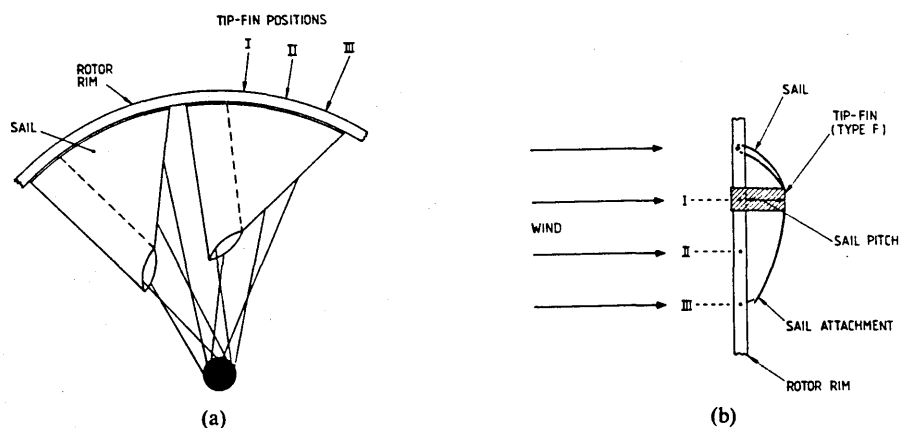


Fig. 60. (a) Rotor segment showing tip-fin position. (b) Tip-fin positions tested and sail profile. (The four dots on the rim represent anchorage points for the wheel spokes.)

EXPERIMENTAL DATA

Horizontal-axis — tip-fins

Table 4.
Tip-fin augmented wind-turbine,
Tested plane or angled tip-fins.
(All were made from 1.5 mm thick dural sheet).

Tip-fin type	Axial and almost circumferential dimensions, respectively (mm × mm)	Description
A	76 × 64	Tip-fin projecting downwind 50 mm from wheel rim.
B	76 × 64	As type A, but 50 mm projection angled at 15° to original wind direction.
C	76 × 64	As type A, but 50 mm projection angled at 7.5° to original wind direction.
D	76 × 64	As type A, but tip-fin projects 50 mm upwind.
E	51 × 165	Circumferentially elongated: projects downwind by 25 mm.
F	102 × 51	Projecting beyond the rim downwind a distance approximately equal to the sail pitch (74 mm).
G	127 × 51	Projecting downwind 25 mm further than type F.
H	229 × 51	Projecting upwind and downwind from the rim a distance approximately equal to the sail pitch (74 mm).

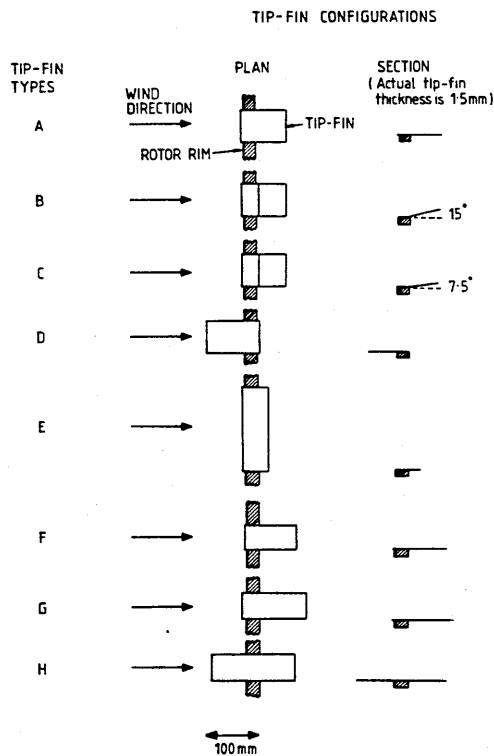


Fig. 61. Tip-fin augmented wind-turbine — tested tip-fins (see also Table 4, above).

EXPERIMENTAL DATA

Horizontal-axis — tip-fins

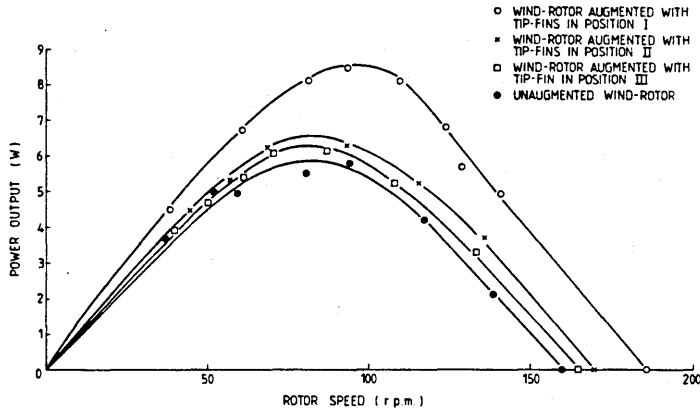


Fig. 62. The influence of tip-fin position on wind-turbine power output characteristics; nine tip-fins, type A, were used throughout.

The optimal tip-fin position was determined using one fin per sail (type A in Fig. 61 and Table 4) in the three different positions (see Fig. 60). The largest power enhancement (see Fig. 62) was achieved with the fins in position I. The tip-fins were able to entrain some of the trailing vortices emanating from the previous sail, as well as create a diffusion down-stream of the rotor. This resulted in a greater air mass flow through the rotor and a greater power output (representing a 47 per cent increase in maximum power harnessed for the position I configuration, relative to that obtained with the non-augmented wind-turbine). In positions II and III, tip losses led to smaller maximum power increases of 11 and 7 per cent respectively.

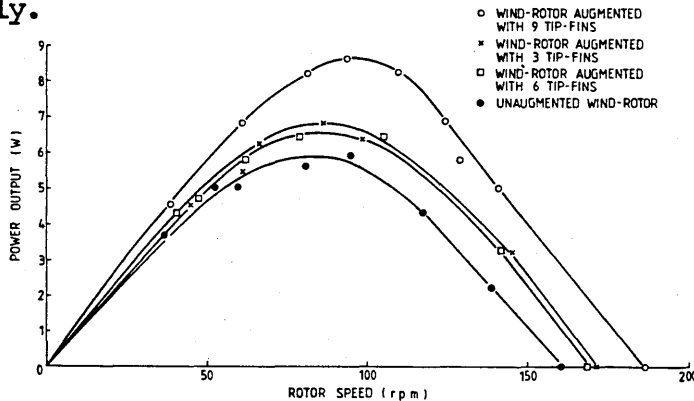


Fig. 63. The dependence of the wind-turbine power output characteristic upon the number of tip-fins, each of type A.

Rotors with three and six tip-fins were then tested. In order to maintain the rotor balance, the six fins were unable to be placed in the same position relative to each of the sails. For the nine sail system considered, three sails were thus without a fin, three sails had tip-fins in position I and three in position III. These were arranged in a radially symmetric configuration. The power characteristics of the six and three tip-fin (type A in Fig. 61) augmented rotor are given in Fig. 63. These both show power increases that were less than those obtained when using nine tip-fins. As each sail was not adjacent to a tip-fin, the trailing vortices were not uniformly diffused down-stream. Thus the diffusion effect was reduced and the power output less, compared with that obtained with the configuration using one tip-fin per sail.

EXPERIMENTAL DATA

Horizontal-axis — tip-fins

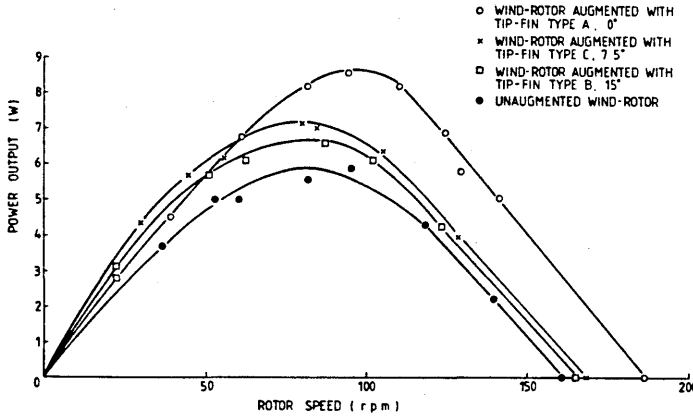


Fig. 64. The effects of tip-fin inclination (to the undisturbed wind direction) upon the wind-turbine power output: nine tip-fins, each in position I were used for this sequence of tests.

Seven other tip-fin arrangements, designated B to H (see Table 4 and Fig. 61) were tested, all with nine fins in position I. Preliminary tests inclining the fins (see configurations B and C) gave 19 and 23 per cent increases in power, for pitch angles of 7.5 and 15 degrees respectively (see Fig. 64). Thus angling the fins in the tested configurations gained no advantage, the induced drag of the protruding fin adversely influencing its ability to diffuse the exhaust air. To a first approximation, this would suggest that zero sail pitch (i.e. flat fins) should be adopted as a good basic preliminary choice.

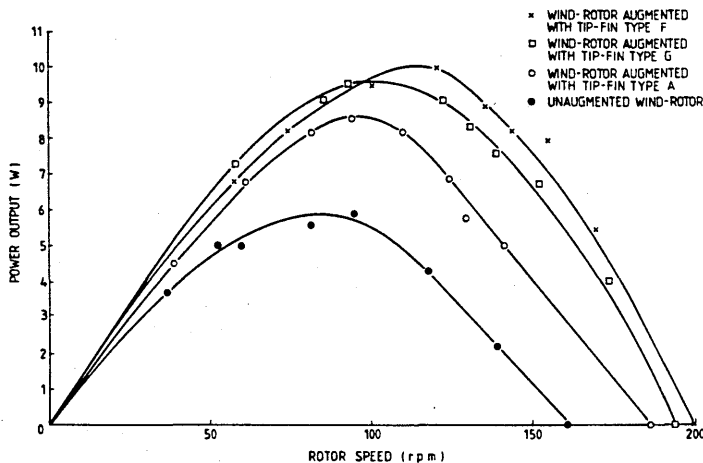


Fig. 65. Wind-turbine power output as a function of tip-fin length: nine fins, each in position I were used.

Two longer tip-fins (type F and G in Fig. 61) were then tested (see Fig. 65). Fin type F projected down-wind of the wind-turbine a distance approximating to the sail pitch, whereas type G projected a further 25 mm. The use of these two fin types led to the largest power increases of the augmentation systems tested. Tip-fin type F interacted with the trailing vortices, deflecting the air that would

EXPERIMENTAL DATA

Horizontal-axis — tip-fins

normally spill out of the sail towards the rotor centre-line, i.e. on to the sail, and so increased the maximum power enhancement by 62 per cent. The type G tip-fin augmented wind-turbine, being slightly longer, induced greater drag forces on the rotor, reduced its rotational speed and so harnessed less wind energy (i.e. a 57 per cent increase in maximum power output). From Fig. 65 it is apparent that the wind-rotor augmented with tip-fin type F harnessed slightly less power, at rotational speeds of less than 100 r.p.m., than did type G. But this disparity is relatively insignificant and overall, greater power was extracted from the wind for a typical torque spectrum with the type F tip-fin augmented wind-turbine.

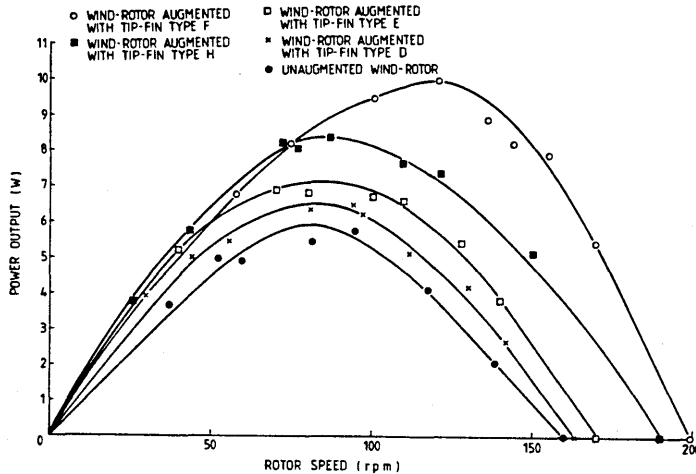


Fig. 66. How wide tip-fins and tip-fins, projecting both up-wind and down-wind, affect the wind-turbine power output characteristics: nine tip-fins, each in position I were adopted.

Placing tip-fin type F up-wind of the wind-turbine (type D in Fig. 61) gave a 15 per cent increase in maximum power harnessment (see Fig. 66). These fins channelled the air that normally flows over the rotor rim, on to the sails, so increasing the mass flow to the rotor. The resulting increase in power output was not as great as when using tip-fins type A (facing down-wind). Diffusing the exhaust air thus gave a greater power enhancement than was achieved by constricting the incoming flow.

The results (Fig. 66) obtained from the wind-turbine configuration employing wide tip-fins (i.e. type E of Fig. 61) gave a maximum power enhancement of 17 per cent. Due to the relatively short projection over the rotor rim, air was able to spill out of the sail over the fin and so be less diffused down-stream. This, combined with the increased drag forces on the relatively large fin, reduced the rotor speed. Hence the power increase was significantly less than that obtained when utilising fins of type A on the rotor.

EXPERIMENTAL DATA

Horizontal-axis — tip-fins

The final tested tip-fins (type H of Fig. 61) projected both sides of the rotor, i.e. both up-wind and down-wind, the same distance as type F, and a maximum power increase of 38 per cent was achieved (see Fig. 66). The reduced power increase (compared with that of tip-fin type F) was due to the large fin projecting up-wind of the rotor. This created additional drag forces on the rotor and so reduced its attainable rotational speed for a given wind velocity. Nevertheless it produced the third greatest power enhancement achieved in the tip-fin augmented wind-turbine series of tests.

12.3.3 Centre-body Augmented Wind-turbine Measurements

The wind speed used for the centre-body (and tip-fin and centre-body — see section 12.3.4) series of tests was approximately 5 ms^{-1} . Due to the crudity of the wind tunnel and the intrinsic difficulties encountered in measuring exactly the wind speed, that recorded in this investigation (and also in the next section 12.3.4) was approximately 0.4 ms^{-1} less than that for the tip-fin only tests (section 12.3.3). However this small (less than 8 per cent) variation in wind speed has a far greater effect upon the power output, which is proportional to the cube of the wind's speed (see Chapter 5 section 5.1). Thus whilst all the augmentation data are readily comparable with the unaugmented wind-turbine observations, direct comparison of section 12.3.2 with 12.3.3 and 12.3.4 cannot be so readily achieved.

Previous research proved inconclusive as to whether the centre-body had a beneficial effect on the performance of horizontal-axis wind-turbines (see Chapter 8, section 8.2.3). This section presents data for the centre-body augmented sail-type wind-turbine.

Three hub-fairings and two after-bodies (see Fig. 67) were tested on the sail type wind-turbine. Figs. 68, 69 and 70, show the power characteristics for the rotor augmented by both rotating and stationary hub-fairings, with and without after-bodies (stationary). Compared with the performance of the unaugmented rotor, the presence of the tested centre-bodies led to increased maximum power outputs. Stationary hub-fairings resulted in greater power increases than rotating ones, whereas all three fairings gave virtually the same power augmentation.

The presence of an after-body also increased the rotor's power harnessing capabilities. But as Blaha (Ref. 11) suggested, its exact shape is relatively unimportant — the two after-bodies tested in this investigation (see Figs. 69 and 70) resulted in similar performance curves and so corroborate Blaha's contention.

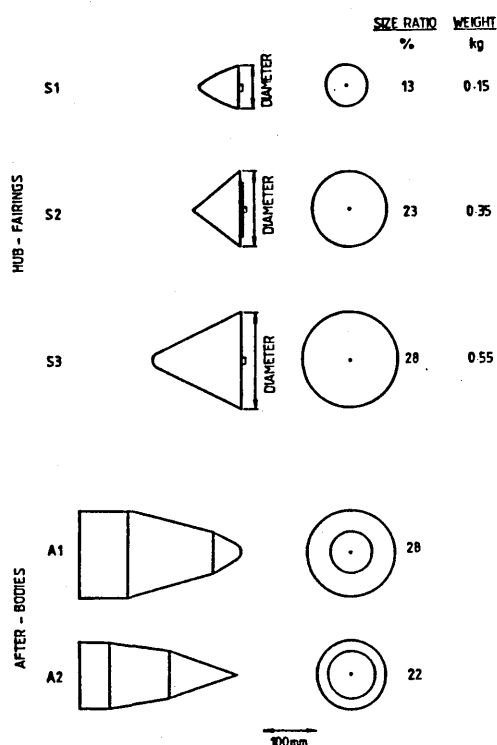


Fig. 67. Dimensions of hub-fairings and after-bodies tested.

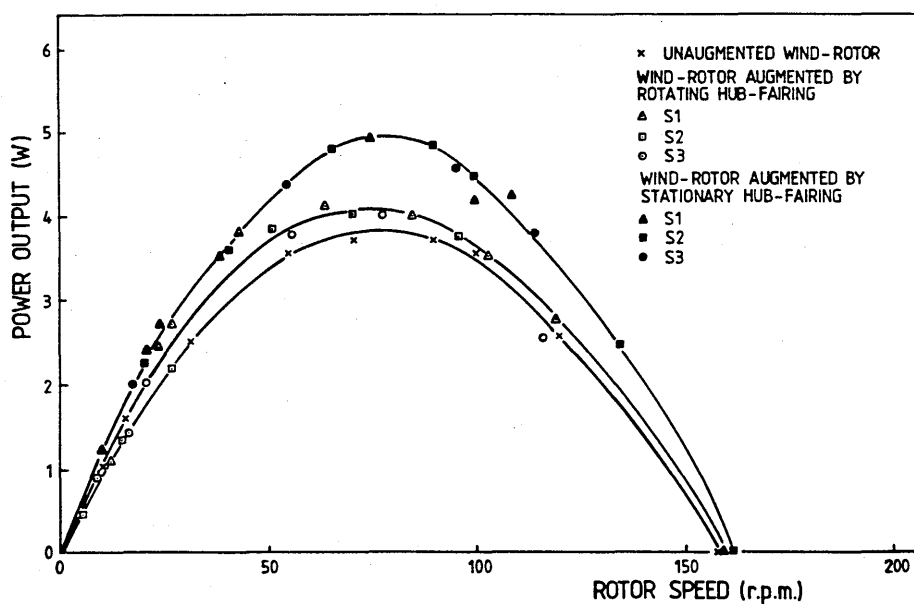


Fig. 68. Power characteristics of the wind-turbine augmented by rotating or stationary hub-fairings with no after-body present.

EXPERIMENTAL DATA

Horizontal-axis — centre-body

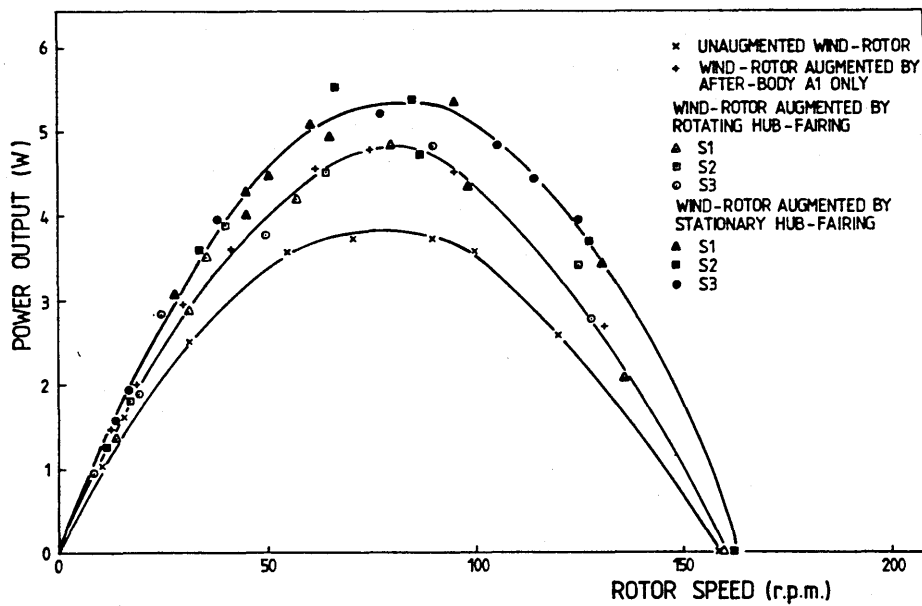


Fig. 69. Power characteristics of the wind-turbine augmented by rotating or stationary hub-fairings with after-body A1 (as shown in Fig. 67).

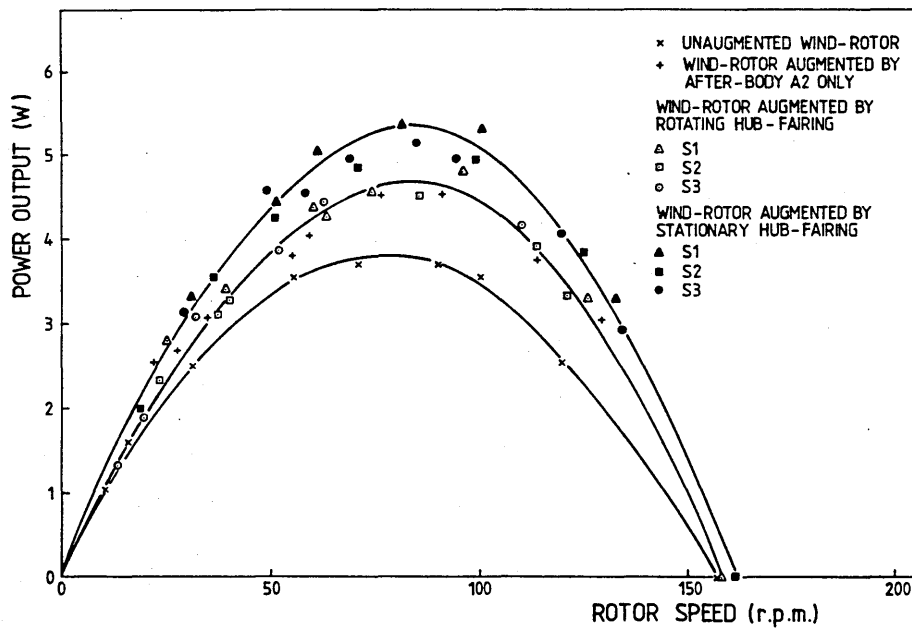


Fig. 70. Power characteristics of the wind-turbine augmented by rotating or stationary hub-fairings with after-body A2 (as shown in Fig. 67).

Horizontal-axis — centre-body

It is also apparent that the shape of the three hub-fairings — chosen as the most suitable (for the present series of tests) of those available — were relatively unimportant, despite their differing weights and size ratios. Indeed, the power characteristics for the wind-rotor and after-body only (see Figs. 69 and 70) are very similar to those of the rotor with the rotating hub-fairing.

The differences between power outputs from rotating and stationary hub-fairing augmented wind-turbines are partly due to the increase in the frictional forces compared with those incurred by stationary hub-fairings. It is recommended that static fairings should be adopted. However they are unlikely to come into widespread use, because to hold both the after-body and the hub-fairing stationary would require slightly more complex, and more expensive, supporting structures. Stationary hub-fairings could be used successfully for designs without after-bodies, where the power take-off mechanism could be enclosed within the stationary fairing.

12.3.4 Tip-fin And Centre-body Augmented Wind-turbine Measurements

Data from augmenting the power output of the wind-turbine by both tip-fins and centre-bodies are presented in the following section. As with the centre-body augmented wind-turbine data (section 12.3.3), the wind speed used was approximately 0.4 ms^{-1} less than the that for the tip-fin augmented wind-turbine data (see section 12.3.2), so negating direct comparison. Nevertheless, these observations are readily comparable with the unaugmented wind-turbine and also with the centre-body augmented rotor.

The centre-body and tip-fin configurations are shown in Figs. 67 and 71 respectively.

Fig. 70 shows the basic performance characteristics of the wind-turbine with various centre-body configurations. These performance characteristics are qualitatively similar to those obtained using the wind-turbine augmented by both a centre-body and tip-fin, see Fig. 69 — the only difference being the larger power outputs achieved as shown in Fig. 72, due to the presence of the tip-fins.

As the centre-body size is relatively unimportant, and the combination of stationary hub-fairing and after-body gives the greatest power enhancement (see section 12.3.3), the further optimisation tests consisted of varying the tip-fin dimensions and attitudes. A centre-body (i.e. the stationary hub-fairing S2 and the after-body, see Fig. 67), was present throughout.

EXPERIMENTAL DATA

Horizontal-axis — tip-fin and centre-body combined

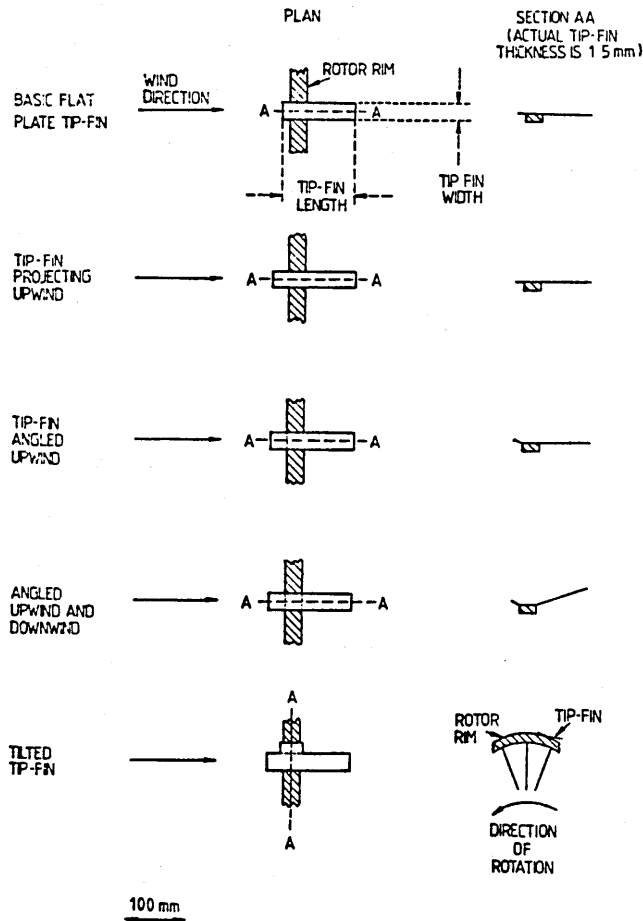


Fig. 71. Tip-fin and centre-body augmented wind-turbine — schematic representation of the tip-fins tested

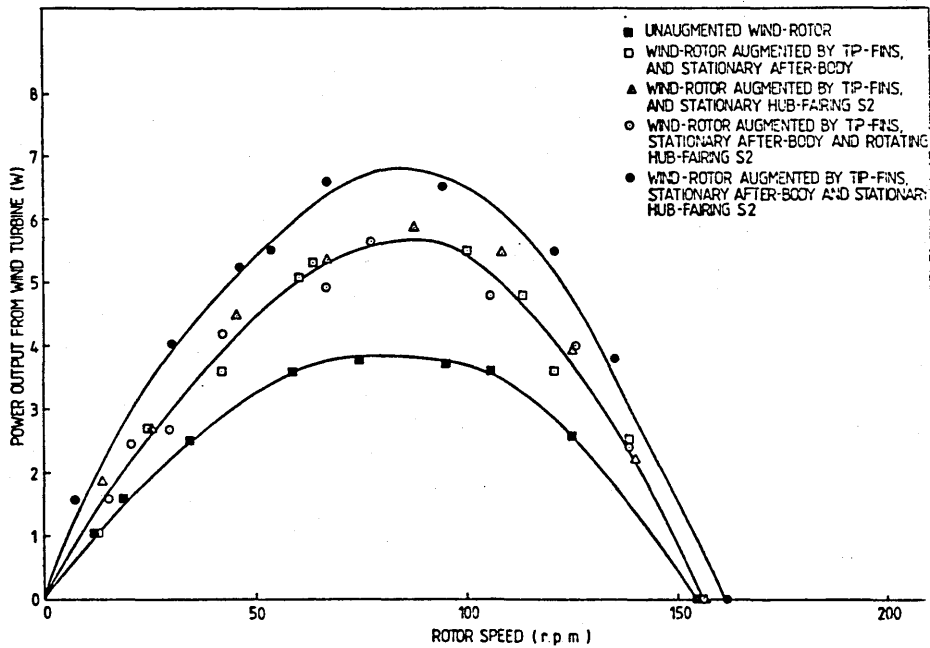


Fig. 72. The effects of centre-bodies and tip-fins on the wind-turbine power output. (Hub-fairing S2 and flat tip-fins 52 mm wide, projecting down-wind by 76 mm were employed for this series of tests).

EXPERIMENTAL DATA

Horizontal-axis — tip-fin and centre-body combined

12.3.4.1 Optimisation Tests -

The optimisation tests were carried out with the 0.64 m diameter wind-turbine augmented by the stationary hub-fairing and the stationary after-body.

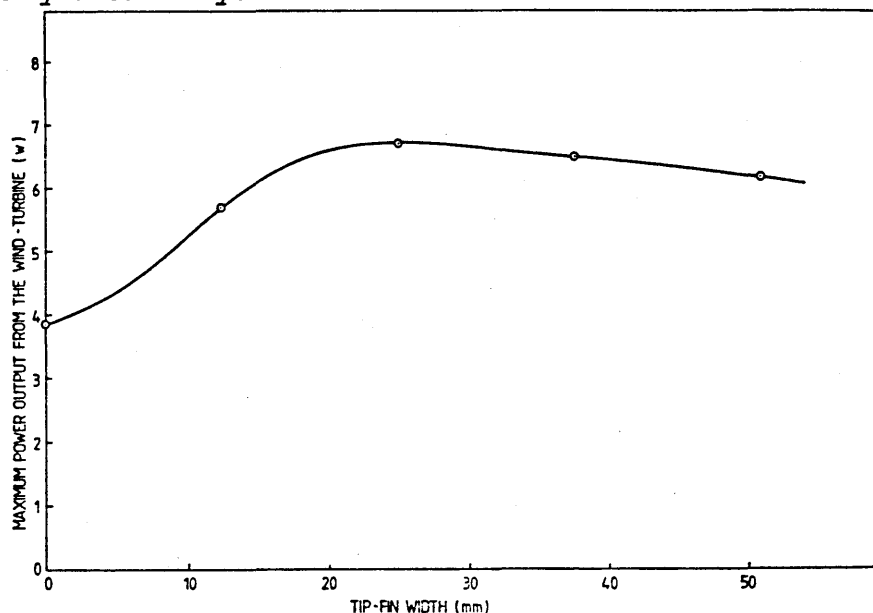


Fig. 73. The effects of tip-fin width on the wind-turbine's maximum power output. The tip-fin length down-wind remained invariant at 76 mm for this sequence of observations.

Fig. 73 shows how the maximum performance of the wind-turbine was affected by tip-fins of various widths. The optimal width was approximately 25 mm. Any fin wider than this resulted in slightly less power being harnessed by the turbine. The smallest practical width was approximately 20 mm (or 1 per cent of the circumference for each of the nine sails). Below this width, the power harnessing capabilities were greatly reduced. For tip-fin widths exceeding 25 mm, the increase in power augmentation due to reducing the fin's width is not explained by the reduction in the mass of the fins. The smaller fins are thought to induce less drag on the wind-turbine, resulting in slightly greater power enhancements, compared with the larger fins.

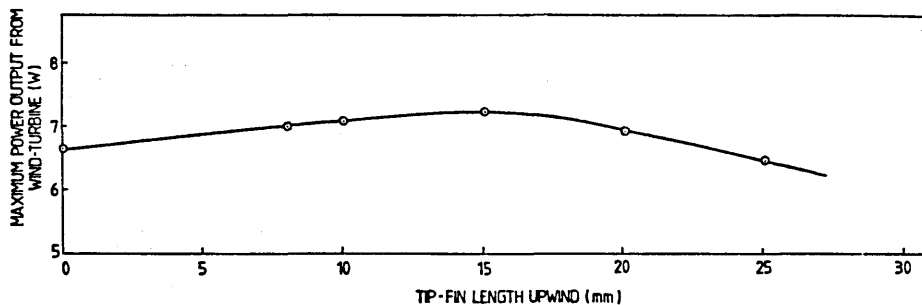


Fig. 74. The influence of tip-fin length up-wind on the wind-turbine's maximum power output. Tip-fins 25 mm wide, projecting 76 mm down-wind were employed in this sequence of tests.

Horizontal-axis — tip-fin and centre-body combined

Previous tests with a relatively large projection (74 mm) up-wind and a relatively wide (51 mm) tip-fin (see Fig. 66), led to harnessing more energy at a particular wind speed than was achievable with the unaugmented wind-turbine, but significantly less than by using the same tip-fins with no projection up-wind. Fig. 74 shows the effect on the wind-turbine's maximum power output of small projections up-wind, the tip-fin width remaining at 25 mm throughout. A slight increase in the maximum power output of the wind-turbine augmented with tip-fins projecting up-wind was observed (compared with that with no projections up-wind); the optimal length being between 10 and 15 mm. These fins, projecting up-wind, tended to entrain the incoming air, so constraining it within the swept rotor's territory, and thereby acting as a simple concentrator.

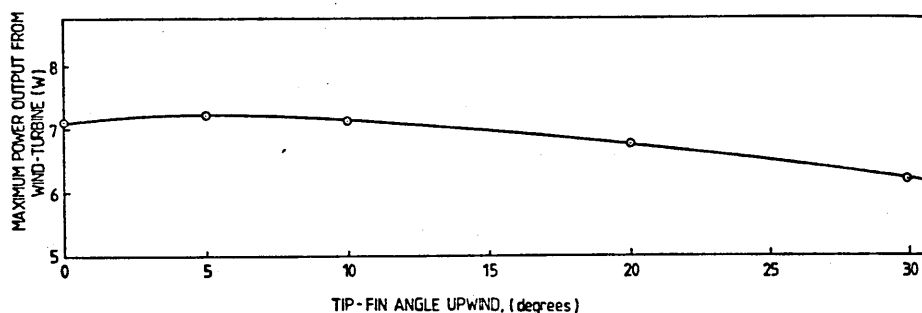


Fig. 75. The effects of tip-fin inclination (relative to the undisturbed wind direction) up-wind on the wind-turbine's maximum power output. Fins 25 mm wide, projecting 76 mm down-wind and 10 mm up-wind were employed in this series of tests.

Tests on the wind-turbine augmented by tip-fins with a 10 mm projection up-wind and inclined outwards (by less than 15 degrees) relative to the axis of the rotor, increased the maximum power output still further (see Fig. 75). The effect of inclining the fin was to enhance the concentration of air achieved. (Comparison should be made with the data presented in Fig. 74 for the system with the flat fins).

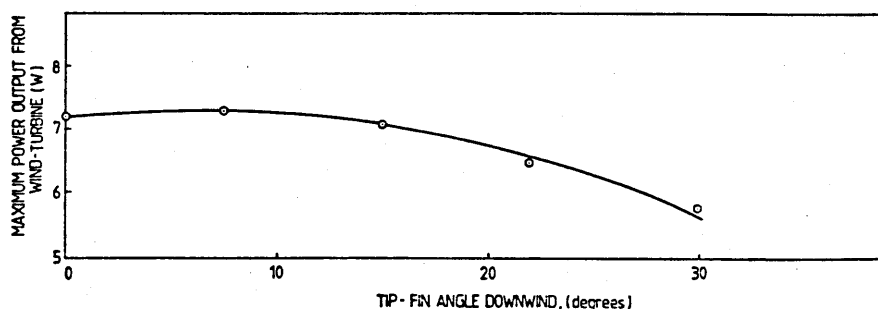


Fig. 76. The influence of tip-fin inclination (relative to the undisturbed wind direction) down-wind on the wind-turbine's maximum power output. Fins 25 mm wide, projecting up-wind by 10 mm at an angle of 5 degrees and projecting down-wind by 76 mm were used.

EXPERIMENTAL DATA

Horizontal-axis — tip-fin and centre-body combined

Inclining the tip-fin down-wind (as well as up-wind), see Fig. 76, also achieved a slight increase in the wind-turbine's power output. Although any angle greater than approximately 10 degrees had an adverse effect on power output. The effect of the angled tip-fin was to enhance the diffusion of the flow down-stream, but with only a relatively small increase in the power so attained. However the extra expense and complexity introduced by inclining the fin may inhibit its more widespread adoption in place of the simpler flat fin.

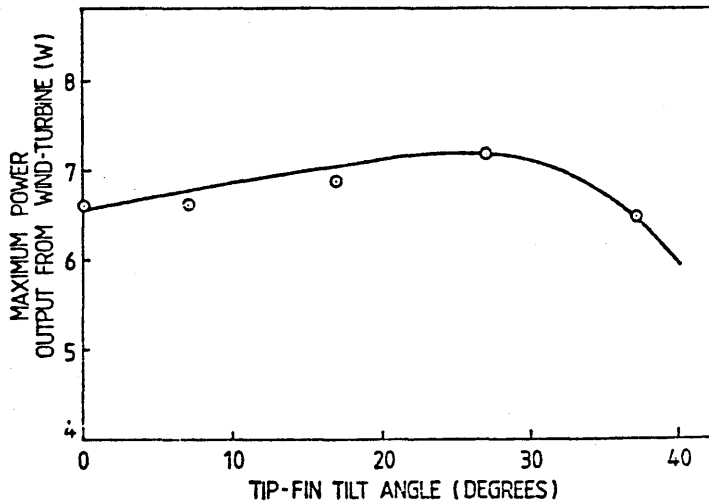


Fig. 77. The influence of tip-fin tilt (relative to the rotor's rim) on the maximum power output. Flat tip-fins, 25 mm wide, projecting up-wind by 10 mm and down-wind by 76 mm were employed.

The effect of tilting the flat fin, which projected up-wind by 10 mm and down-wind by 76 mm, is shown in Fig. 77. The tip-fins were tilted with respect to the tangent to the wind-turbine rim, in the plane of the rotor (see Fig. 71), i.e. outward from the rotor's circumference. The wind-turbine augmented with these tilted fins showed significant power augmentations, but the tip-fins tilted (oppositely) into the direction of rotation led to lower power enhancements. This occurred because these oppositely tilted fins created larger drag forces on the rotor, so significantly reducing its rotational speed, hence decreasing the power harnessed from the wind. Although Fig. 77 shows that tilting the fin through an angle of 20 to 30 degrees gives the greatest power output from the wind-turbine, this power augmentation is less than that achieved with the tip-fin projecting and angled both up-wind and down-wind (see Fig. 76). Thus on the basis of maximum power output, the tilted, flat fins are less effective than those inclined fins that project up-wind by 10 mm and 5 degrees and down-wind by 76 mm at 7.5 degrees.

EXPERIMENTAL DATA
VERTICAL-AXIS WIND-TURBINE

12.4 VERTICAL-AXIS WIND-TURBINE

The wind-turbine was constructed using two aluminium discs connected by a series of vertical rods (see Plate 5). The use of the rods was to allow the sail to "run" or "flow" over these rods relatively easy, so facilitating simple changes of the sail's profile, relative to the wind's direction (see Chapter 9, section 9.3). The two 0.584 m diameter aluminium discs were drilled to fit the various sail curvatures tested (see Fig. 78). Support rods were then placed through these holes, thereby maintaining a constant 0.584 m separation between the plates.

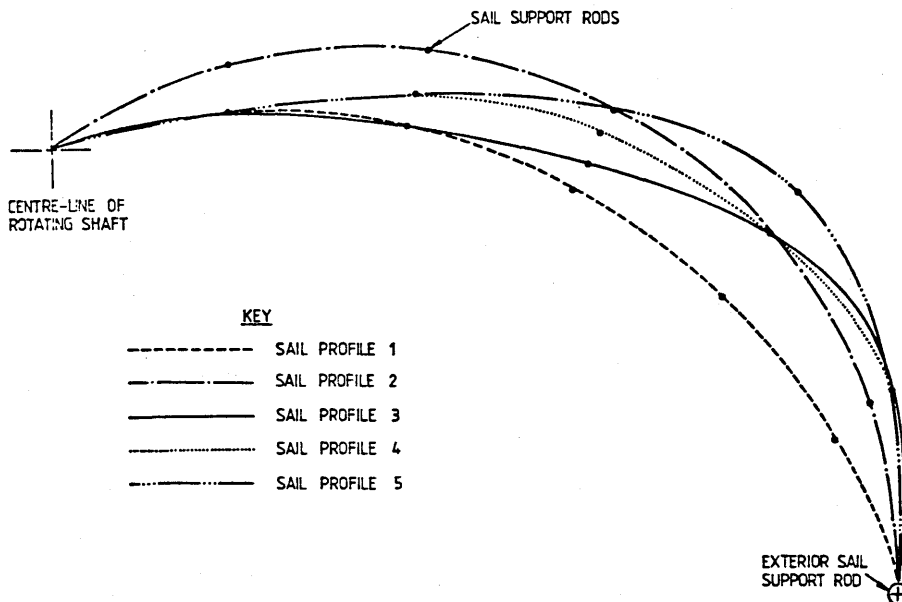


Fig. 78. Outline of the Savonius sail profiles tested — the sail material is rip-stop nylon.

The frame was designed to support the wind-turbine symmetrically, with the rotor axis orthogonal to the wind tunnel axis. It also enabled the rotor to be easily dismantled to facilitate altering the controllable experimental variables. Horizontal cross-members, containing the bearing assemblies (see Figs. 44, 45 and Plate 5) were designed to permit the removal of the end-plates for the testing of different sail profiles.

EXPERIMENTAL DATA
Vertical-axis

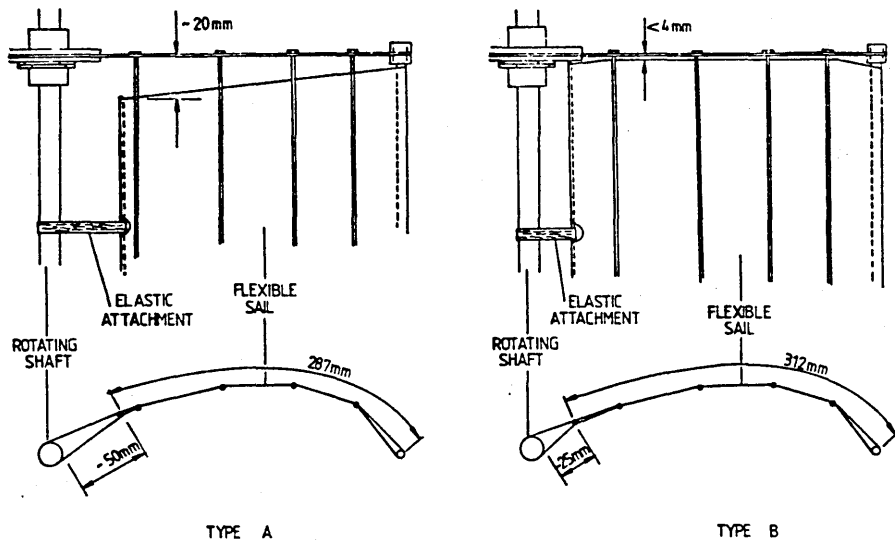


Fig. 79. Savonius wind-turbine — sail types A and B with elastic attachments

Fig. 79 shows the two different types of sails tested. Type A, a short sail designed to prevent interference between the sail and the end-plates, and type B, a wider sail (leaving a small central gap of 50 mm) with minimal clearance between the sail and the end-plate.

Flexible sails provide a degree of self-regulation in high speed winds. The elastic fastenings connecting the sails to the central shaft (see Fig. 78) would "yield" under such conditions and allow the sail to "spill the wind" so preventing over-speed, which would probably damage the wind-turbine.

For the wind-turbine to operate successfully with the varying sail profiles, deflectors may be required (see Fig. 80). The purpose of these is to enable relatively short sails to be employed, so allowing the sails to flow freely over the rods, i.e. without catching against the end-plates especially the lower one. The deflector, plus a "short" sail would thus have the same effect as the longer sail, but without the inherent associated friction problems between the sail and the end-plate when the sail moves over the rods.

The first series of data presented (Figs. 81 to 84), is for determining the working sail profile, i.e. that rotating with the wind. The second series of tests (Fig. 85), allowed the sails to take up the optimal profiles derived in Figs. 81 to 84. Fewer support rods would be needed to define this optimised profile, i.e. only to force the wind to constrain the sail shape to the optimal "momentum capture" profile. The function of the support rods here would be to define the sail shape for minimum resistance to the wind, so creating the variable sail profile Savonius wind-turbine.

EXPERIMENTAL DATA
Vertical-axis

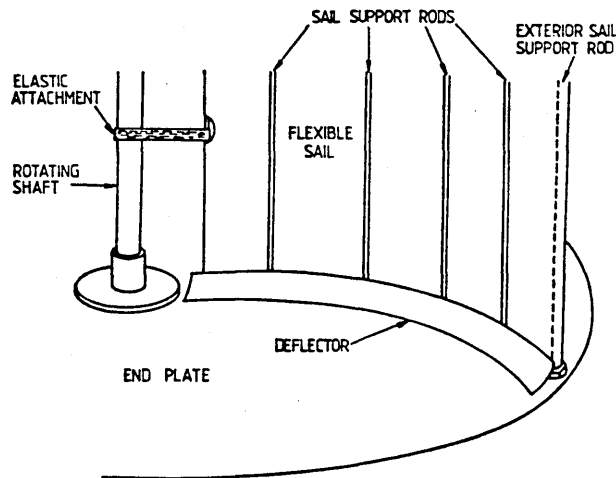


Fig. 80. Savonius sail deflector for "short" sails.

Firstly, tests of various sail profiles and sail areas were undertaken in order to obtain a "base" performance characteristic with which to compare the variable sail profile wind-turbine.

Corrections for wind tunnel interference for the Savonius wind-turbine were considered to be too large to be trust-worthy (see Chapter 11 section 11.1.2), accordingly, all data are presented uncorrected for wind tunnel interference. Also, the equivalent "free-air" wind speed was not readily determined, so, as with the horizontal-axis series of tests (see section 12.3), all data are presented on a comparative basis only, for a wind speed approximately equal to 5 ms^{-1} . Power coefficient versus tip-to-wind speed ratios are thus not presented, but rather power versus rotational speed, to allow direct comparisons with the various rotor characteristics tested.

12.4.1 Taut Sail Profile Vertical-axis Wind-turbine Measurements

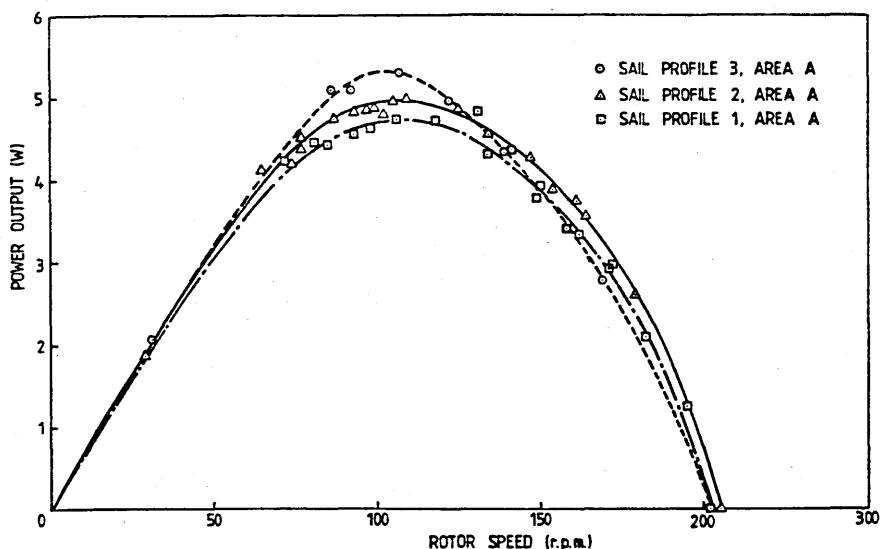


Fig. 81. The effect of sail profile on the Savonius wind-turbine's power outputs: sail area A (see Fig. 79).

EXPERIMENTAL DATA

Vertical-axis — taut sail profile

Fig. 81 shows the results obtained from testing sails of type A (see Fig. 79) in three different profiles, (1, 2 and 3 in Fig. 78). The three profiles all exhibit similar power characteristics with profile 3 giving a slightly higher maximum power output at a rotational speed of 110 r.p.m.

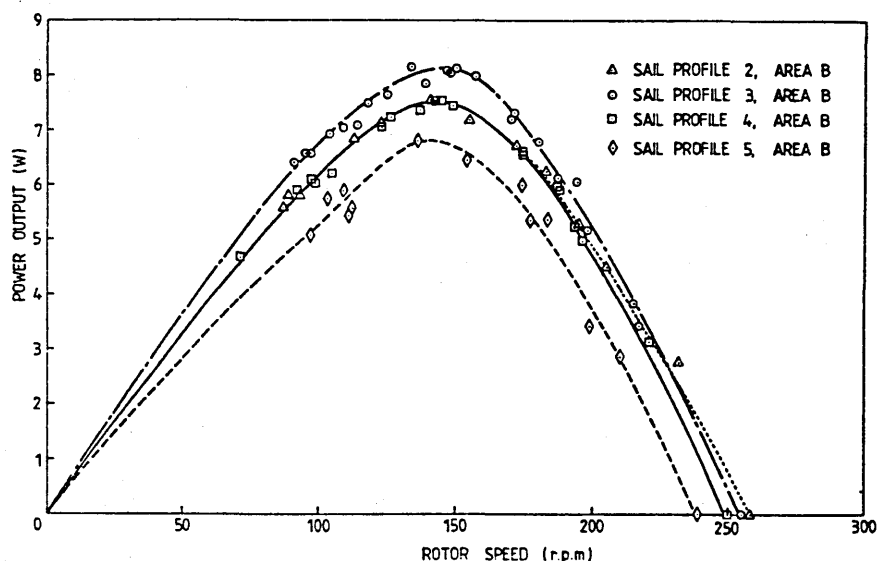


Fig. 82. The effect of sail profile on the Savonius wind-turbine's power outputs: sail area B (see Fig. 79).

The effect of a higher solidity rotor is shown in Fig. 82. For this, two slightly "deeper" sail profiles were tested (see profiles 4 and 5 in Fig. 78). Again all the sail profiles have similar performance curves, with profile 3 giving the greatest maximum power. The power characteristics of profiles 2 and 4 are indistinguishable, whereas profile 5, the "deepest" curve shows approximately 20 per cent less power than profile 3 and this is harnessed at a rotor speed of 150 r.p.m. — this speed approximately corresponds to the speed at which maximum power output occurs for all the sail profiles.

These variations in power output between the "circular" and the "deep" profiles (see Fig. 78) are considered unique to three-sail Savonius wind-turbines. The "deeper" curves have been used successfully with metal two-bladed rotors and their poor performance characteristics here are probably due to the interference of the wind flow on to the momentum capture sail by the next sail interrupting the flow. This interference (which is most apparent with sail profile 5) thus tends to ensure that the greater power outputs are attained with rotors possessing shallower curved sails. This obstruction occurs with both curves 4 and 5. Sail profile 5 exhibits poor performance characteristics and profile 4 (a slightly shallower profile) shows power outputs almost identical with those of the circular profile 2. Profile 3 is not a circular profile, but neither is it a very deep one. It is sufficiently shallow for the problems associated with profiles 4 and 5 not to manifest themselves.

EXPERIMENTAL DATA

Vertical-axis — taut sail profile

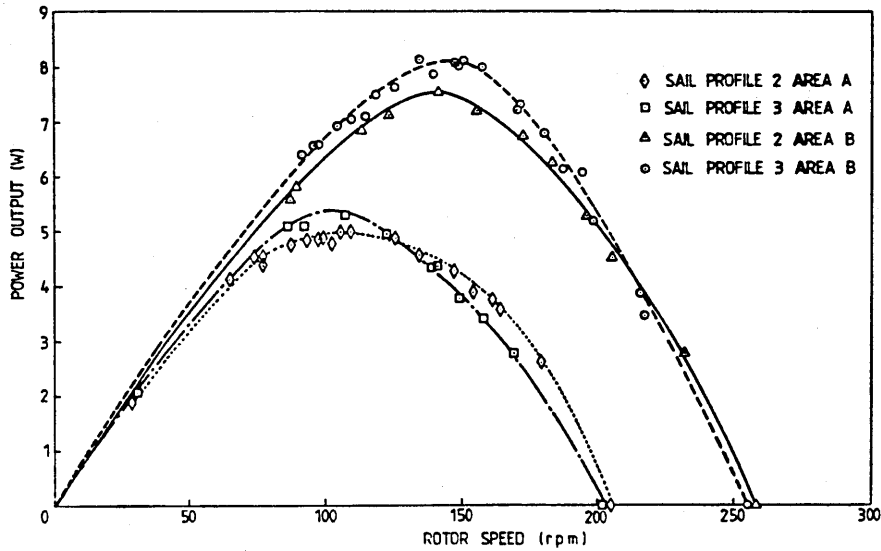


Fig. 83. The effect of solidity on the Savonius wind-turbine's power outputs: sail profile 3 (see Fig. 78).

Comparing sail profile 3 for wind-turbines with both sail types A and B (see Fig. 83), clearly demonstrates the superior power harnessing qualities of the higher solidity turbine. This gives approximately 60 per cent greater maximum power, at a rotational speed of 150 r.p.m. (compared with 110 r.p.m. for sail area A). Thus it is apparent that the solidity of the wind-turbine is a far more important determinant of power output, than sail profile.

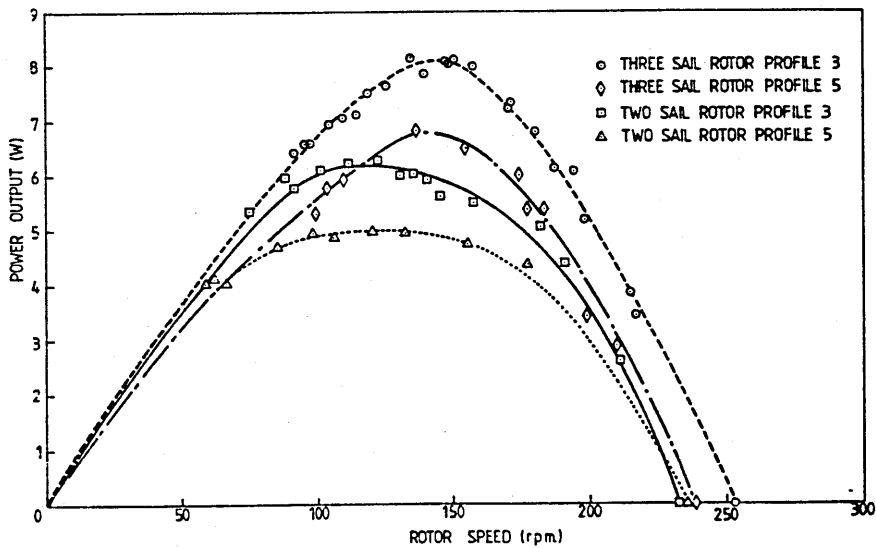


Fig. 84. Comparison of the power outputs for two- and three- sail Savonius wind-turbines.

EXPERIMENTAL DATA

Vertical-axis — taut sail profile

Tests were undertaken to compare the power outputs of two- and three- sail Savonius wind-turbines. These show (see Fig. 84) an increase of approximately one third in maximum power outputs for a three-sail wind-turbine for sail profiles 3 and 5. This result is contrary to the findings of Shankar (Ref. 69), who recorded increases in power output of the order of 50 per cent for two-vaned rotors compared with three-vaned. This large discrepancy is not completely accounted for by the fact that Shankar used rigid blades, whereas the tests presented here were using flexible sails. Other factors, such as the central gap setting for the two-sail rotors also contributed — the dimensions of the central gap are considered to be relatively unimportant with the three-sail rotors, but not for two-sail ones. Thus it is expected that the performance characteristics of the two-sail rotor in Fig. 84 could be significantly improved by reducing the central gap.

12.4.2 Variable Sail Profile Vertical-axis Wind-turbine Measurements

The light-weight "rip-stop" nylon used for the taut sail profile tests proved too flexible for use with the variable sail profile rotor (see Chapter 9, section 9.3). The fabric formed "cups" between the support rods so resulting in increased rotor resistance when rotating against the wind and hence the wind-turbine exhibited very poor power characteristics. Employing a more rigid sail cloth (4.5 oz), prevented this occurring. Observations of the wind-turbine at low rotational speeds clearly showed the sails changing their profile relative to the wind direction, without the sails "collapsing" between the rods.

Whilst the concept of the variable sail profile was simply demonstrated, preliminary tests showed that the power so harnessed by the rotor was poor (of the order of 2 W maximum in the 5 ms⁻¹ wind speed). This was due to a combination of several factors, the major two of which were;

1. the sails tended to oscillate vertically during each rotation of the wind-turbine, allowing air to pass directly through the rotor; so not harnessing the energy it contained, and
2. frictional effects of the sails passing frequently over the rods and the increase in noise levels, dissipated otherwise useful energy.

In an attempt to reduce the vertical sail movement, sail deflectors (see Fig. 80) were used at the top and bottom of each of the three sails. This reduced the actual sail area, but held constant the "useful sail area" opposed to the wind. Deflectors made from the sail cloth proved ineffectual, so metal ones were used. These were larger than those depicted in Fig. 80) — having an area of 0.009m² exposed to the air flow — and were made of 1.5 mm thick dural.

EXPERIMENTAL DATA

Vertical-axis — variable sail profile

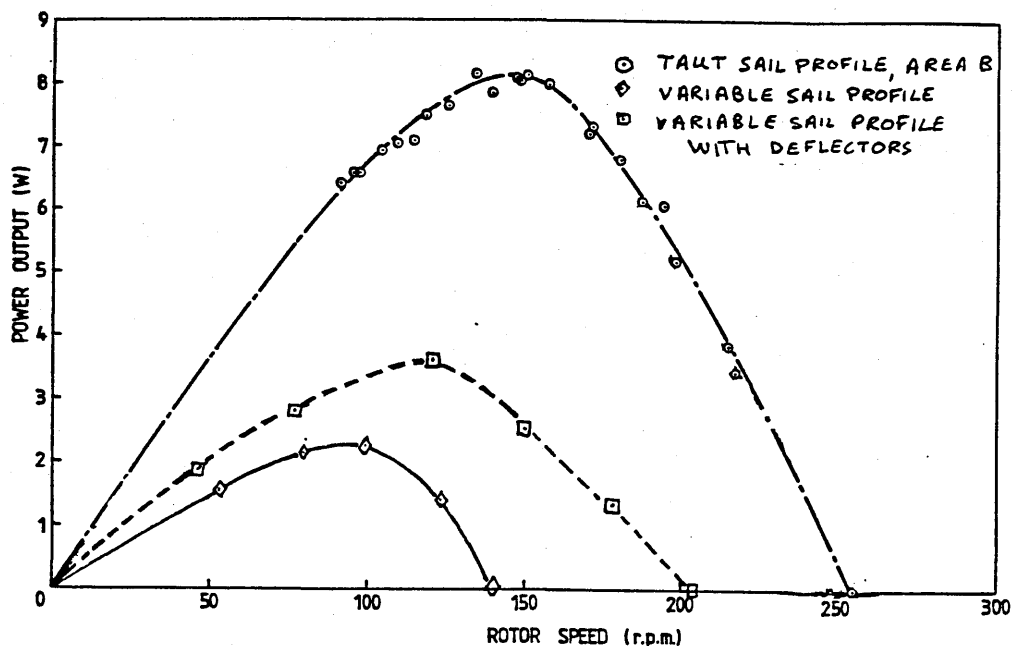


Fig. 85. Power characteristics for the Savonius wind-turbine with a taut sail profile and with a variable sail profile.

Fig. 85 shows the power characteristics of such a variable sail profile wind-turbine with deflectors, compared with those of the taut sail profile rotor. The variable sail profile wind-turbine is extremely poor at harnessing the wind's energy. Data were obtained using a variety of sail areas and sail attachment lengths. The sail length (which is proportional to the sail area) was varied between 0.53 m and 0.55 m, and the attachment length between 35 mm and 55 mm. All the data so derived fell roughly on the variable sail profile rotor curve shown in Fig. 85.

Hurley's (Ref. 21) variable sail profile Darrieus-type wind-turbine operates far more effectively than the tested Savonius rotor because it works on lift, rather than drag forces. This rotor has no end-plates, so avoiding sail interference problems. Also the whole sail arrangement (see Fig. 3) changes its position relative to the wind direction. The tested Savonius wind-turbine suffered increased frictional losses as only the sail, and not the rods, change position relative to the wind direction. The sails of Hurley's rotor rotate only at the periphery of the circle described by the rotating turbine and so do not suffer the relatively complicated air flow pattern near its central shaft, as the sail changes its shape.

Thus whilst the variable sail profile wind-turbine concept is a viable one (see e.g. the early Chinese rotors (Ref. 35) and that of Low Energy Systems (Ref. 21)), it is not applicable to the three-sail Savonius wind-turbine tested here. Accordingly this particular variable sail profile is not recommended for use with the sail-type Savonius wind-turbine.

CHAPTER 13

CONCLUSIONS

13.1 CONCLUSIONS

Small wind-turbines are readily accepted in developing countries, as prime movers for raising water. They have a vast potential world market and are becoming increasingly more economically viable, compared with other power sources.

Sail-type wind-turbines driving relatively low technology water pumps, included as part of a "Western aid package", could greatly improve the living standards of rural populations far more cost-effectively than most current "aid" programmes.

Mathematical analyses describing the behaviours of propeller-type wind-turbines are comprehensive and well documented, but those for flexible-sail rotors are still in their infancy. The theoretical analyses of the aerodynamic behaviour of yacht sails contributes to our understanding, but, as yet, no definitive mathematical model exists to describe flexible sail wind-turbine performance.

The presence of a shroud on a wind-turbine leads to the greater percentage extraction of the available energy from an identical wind, compared with an unaugmented wind-turbine. But the shroud is unlikely to find widespread use with low cost sail-type wind-turbines; the initial high capital cost of the shroud far outweighs any subsequent power generating advantages.

Tip-fin augmentation, whilst not enhancing wind-turbine power outputs to as great an extent as a shroud, is a far more cost effective method of power augmentation.

Rotating hub-fairings are capable of augmenting the power outputs of sail-type wind turbines. However, holding the hub-fairings stationary results in even greater power outputs.

An after-body on its own (without a hub-fairing) gives approximately the same power harnessing capabilities as a conventional centre-body configuration (i.e. rotating hub-fairing and static after-body).

CONCLUSIONS

Conclusions

The shapes of the hub-fairing and after-body are relatively unimportant with respect to augmenting the wind-turbine power outputs.

The simultaneous use of both tip-fins and a centre-body increases the power augmentation of the flexible-sail wind-turbine more than by using either of the two augmentation devices alone. However, the overall percentage effect of combining them is less than the sum or their respective power augmentation percentage improvements when each is used alone.

For the wind speed of 5 ms^{-1} adopted, the optimal dimensions and attitude of the tip-fins for the centre-body augmented wind-turbine are:-

1. Width — each between 20 and 25 mm (or 1 to 1.2 per cent of the wind-turbine circumference);
2. Length down-wind — 76 mm angled at approximately 7.5 degrees to the wind direction
3. Length up-wind — Between 10 and 15 mm angled at approximately 5 degrees to the wind direction.

Tilting the optimised FLAT tip-fins through an angle of 20 degrees to the tangent to the rotor circumference, whilst significantly increasing the wind-turbine's maximum power output, did not do so to as great an extent as the optimised fins described above.

Because the optimal tip-fin to achieve maximum power augmentation of the 0.64 m diameter centre-body augmented wind-turbine, is relatively complicated in shape, the additional cost to produce such fins may discourage their widespread adoption. In such a situation a flat fin tilted through 20 degrees may be more appropriate.

The simple, cheap power augmentation devices tested here for this small, prototype horizontal-axis sail-type wind-turbine are capable of almost doubling its power output. Further tests are required to ascertain the commercial viability of these basic power augmentors for employment with larger (i.e. greater than 2.5 m diameter) flexible sail wind-turbines.

For the vertical-axis wind-turbine, solidity is far more critical than sail profile in determining power outputs. For the three-sail wind-turbines, "deep" and "circular" arc profiles give relatively poor performance characteristics. The optimal profile lies in between these two extremes and possesses a "shallow" curvature.

The variable sail profile Savonius-type wind-turbine is poor at harnessing the wind's energy. The taut sail profile rotor gives greater power outputs, as the frictional effects of the changing sail profile and the relatively complex air flows caused at the central shaft dissipate otherwise usefully harnessed energy.

CONCLUSIONS

Conclusions

Despite the official United Kingdom governmental bias towards large scale, electricity generating wind-turbines, research and development concerning small scale wind-turbines is becoming increasingly recognised as a vital and productive area of wind energy utilisation. Thus using the cheap, basic power augmentation devices reported in this investigation, could significantly increase the cost-effectiveness of sail-type wind-turbines, making them even more attractive for use in areas where conventional fuel costs are at a premium.

13.2 RECOMMENDATIONS FOR FUTURE RESEARCH

1. The implementation of a "wind-pump" demonstration project, as outlined in Appendix D.
2. Developing a mathematical model to describe the behaviours of wind-turbine flexible sails.
3. Designing a low technology wind-pump — in particular, optimising the design of the Robertson-Leaman pump to suit an augmented flexible sail wind-turbine.

REFERENCES

1. S.K. TEWARI, "An evaluation of the strategy of low-cost, horizontal-axis windmills", Proceedings of the International Solar Energy Congress, Sun: Mankinds future source of energy, New Dehli, India, Vol. 3, pp. 16-21, 1978.
2. Th. van HOLTEN, "Concentrator systems for wind energy, with emphasis on tip-vanes", Wind Engineering, Vol. 5, No. 1, pp. 29-45, 1981.
3. M.M. SHERMAN, "The design and construction of low cost wind powered water pumping systems", Proceedings of the Meeting of the Expert Working Group on the use of Solar and Wind Energy, pp. 76-104, Energy resources Development Series, No. 16, United Nations, New York, 1976.
4. M.M. SHERMAN, "Development of wind energy utilisation in Asia and the Pacific", Proceedings of the Expert Working Group on the use of Solar and Wind Energy, Energy Resources and Development Series No. 16, United Nations, New York, pp. 61-65, 1976.
5. P. FRAENKEL, "Food from windmills", Intermediate Technology Publications, London, 1975.
6. S.K. TEWARI, N. INGAIAH, D.V.V SUBRAMANYAM and A.C. SCAMRAJ, "Horizontal-axis sail windmill for use in irrigation", Proceedings of the Indian Academy of Science, Section C, Vol. 2, Pt. 1, pp. 107-116, 1979.
7. Th.A.H. DEKKER, "Performance characteristics of some sail and steel-bladed wind rotors", Steering Committee for Wind Energy in Developing Countries, Amersfoort, The Netherlands, 1977.
8. N.G. CALVERT, "The characteristics of a sail mill", Journal of Industrial Aerodynamics, Vol. 3, No. 1, pp. 79-84, 1978.
9. O. IGRA "Preliminary results from the shrouded wind-turbine pilot plant", Journal of Energy, Vol. 4, pp. 190-192, 1980.
10. K.M. FORMAN and B.L. GILBERT, "Technical development of the diffuser augmented wind-turbine, (DAWT) concept" Wind Engineering, Vol. 3, pp. 153-166, 1979.
11. R. BLAHA "The effect of a centre-body on axial flow windmill performance" AMS Report 1266, Princeton University, New Jersey, 1978.
12. R.A. WILLEM, "A wind energy review: wind machines for agricultural and rural applications", Caribbean Consultation on Energy and Agriculture, (Bilingual Edition), Instituto Superior de Agricultura, Dominican Republic, pp. 408-417, 1980.

REFERENCES

13. S.J. SAVONIUS, "The S rotor in theory and practice" Savonius and Company, Helsingfors, Finland, 1926.
14. ANONYMOUS "Home built, Savonius oil-barrel rotor", National Centre for Alternative Technology, Machynlleth, Powys, Wales, 1977.
15. M.H. SIMMONDS and A. BODEK, "Preformance test of a Savonius rotor", Brace Research Institute, Report No. TR10, McGill University, Canada, 1964.
16. B.F. BLACKWELL, W.N. SULLIVAN, R.C. REUTER and J.F. BANAS, "Engineering development status of the Darrieus wind-turbine" Journal of Energy, Vol. 1, No. 1, pp. 50-64, 1977.
17. A. SABZEVARI, "Power augmentation in a ducted Savonius rotor", Second International Symposium on Wind Energy Systems, Amsterdam, The Netherlands, BHRA Fluid Engineering, 1978.
18. S. SIVASEGRAM, "Concentration augmentation of power in a Savonius-type wind-rotor", Wind Engineering, Vol. 3, pp. 52-61, 1979.
19. D.V. NGUYEN, "Comparative performance measurements on a Savonius rotor with ancillary surfaces" Wind Engineering, Vol. 3, pp. 115-120, 1979.
20. J.S. CAMPBELL "The Campbell Chinese type windmill", Sun: Mankind's future source of energy, Proceedings of the international Solar Energy Congress, New Delhi, India, Vol. 3, pp. 1790-1795, 1978.
21. B. HURLEY, "A vertical-axis sail windmill" Low Energy Systems, Dublin, 1978.
22. B.G. NEWMAN and T.M. NGABO, "The design and testing of a vertical-axis wind-turbine using sails", Energy Conservation, Vol. 18, No. 3, pp. 141-154, 1978.
23. E.H. LYSEN, H.G. BOS and E.H. CORDES, "Savonius rotors for water pumping", Steering Committee for Wind Energy in Developing Countries, Amersfoort, The Netherlands, 1978.
24. S.P. GOVINDA RAJU and R. NARASIMHA, "A low cost water pumping windmill using a sail-type Savonius rotor" Proceedings of the Indian Academy of Science, Vol. C2, pt. 1, pp. 67-82, 1979.
25. R.E. WILSON, P.B.S. LISSAMAN and S.N. WALKER, "Aerodynamic performance of wind-turbines" Final Report, ERDA/NSF 04014-76/1, Oregon University, U.S.A., June 1976.
26. W.M. JANSSEN and P.T. SMULDERS, "Rotor design for horizontal-axis windmills" Steering Committee for Wind Energy in Developing Countries, Amersfoort, The Netherlands, 1977.

REFERENCES

27. C.A. MARCHAJ, "Instability of sailing craft — rolling" Proc. III American Institute for Aeronautics and Astronautics Symposium on the Aero/hydronautics of sailing, Vol. 10, pp. 30-71, AIAA, Los Angeles, 1971.
28. H. KAY, "The science of yacht, wind and water", G. T. Foulis and Company Ltd., Henley on Thames, Oxfordshire, 1972.
29. AYOB BIN SUKRA, "Personal communication", Agricultural Engineering Branch, MARDI, Malaysia, Jan 1983.
30. R. BENNETT and J. ELTON, "History of corn milling", Vol.2, Howell, Liverpool; Simpkin, Marshall and Company Ltd., London, 1899.
31. C. SINGER, E.J. HOLYWARD, A.R. HALL and T.I. WILLIAMS, "A history of technology", Vol.2, Clarendon Press, Oxford, 1965.
32. HERON OF ALEXANDRIA, "Spiritalium liber", Mechanici, Venice 1572 and Urbino, 1575.
33. W. SCHMIDT, "Heron of Alexandria's Pneumatica", Vol.1, Tuebner, Leipzig, 1899.
34. M.H. MORGAN, "Vitruvius: the ten books on architecture", Harvard University Press, Cambridge, Mass., 1914.
35. J. NEEDHAM, "Science and civilisation of China", Vol.4, Pt.II, Cambridge University Press, London, 1965.
36. A. CLARKE, "More windmill land", J. M. Dent and Sons Ltd., London, 1917-18.
37. KAUTILYA, "Arthasastra", circa. 400 B.C.
38. N.N. LAW, "Studies in ancient Hindu polity", Longmans, Green and Co., London, 1914.
39. A. FLETTNER, "The story of the rotor", Crosby, Lockwood and Son, London, 1926.
40. M.F. MERRIAM, "Wind energy for human needs", Lawrence Berkeley Laboratory, University of California, 1974.
41. H.P. VOWELS, "An enquiry into the origin of the windmill", Transactions of the Newcomen Society, Vol.11, pp. 1-14, 1930.
42. R. WAILES, Discussion appearing with reference 12.
43. H.T. HORWITZ, "Über das aufkommen, die erste enwicklung und die vertbreitung von windraden", BGTI/TG, Vol.22, 1933.
44. J. BECKMAN, "History of inventions, discoveries and origins", (Translated from the German by W. Johnstone), Vol.1, J. Bell, London, 1797.
45. S. FREESE, "Windmills and millwrighting", Cambridge University Press, London, 1957.

REFERENCES

46. H.P. VOWELS and M.W. VOWELS, "The quest for power", Chapman and Hall Ltd., London, 1931.
47. J. DE BRAKELOND, "Memorials of St. Edmunds Abbey", Edited by T. Arnold, Chronicles and Memorials of Great Britain and Ireland, Rolls Series, HMSO, London, 1890.
48. L. WHITE, Review of the second edition of A.P. Usher's, "A history of mechanical inventions", ISIS, Vol.46, pp. 290-293, 1955.
49. G. BATHE, "Horizontal windmills, draft mills and similar air-flow engines", Allen, Lane and Scott, Philadelphia, 1948.
50. R. WAILES, "Horizontal windmills", Transactions of the Newcomen Society, Vol.60, pp. 125-145, 1967-1968.
51. J. SMEATON, "On the construction and effects of windmill sails", Proc. Royal Society, pp. 100-173, London, 1759.
52. E.N. FALES, "Propeller design as applied to windmills" Journal of Aeronautical Science, Vol. 3, pp. 278-281, 1936.
53. ANONYMOUS, "Aerodynamic wind mills", Scientific American, p. 525, June, 1929.
54. G.J.M. DARRIEUS, "Turbine having its rotating shaft transverse to the flow of the current", US Patent No. 1,835,018, 1931.
55. P.C. PUTMAN, "Power from the wind" Van Nostrand Reinhold, New York, 1948.
56. P.E. MONTAGNON and E.W. GOLDING, "The development of a 100 kW wind power plant in the United Kingdom", Paper presented to the British Electrical and Allied Industries Research Association, Madrid, Spain, June 6, 1960.
57. L. VADOT, "Etude synoptique des differents types d'eoliennes", La Houille Blanche, Vol.12, pp. 204-212, 1957.
58. D. ELLIOT, "Economic wind power", Applied Energy, Vol. 1 pp. 167-197, 1975.
59. G. LACROIX, "Les moteurs a vent, les eoliennes electrique Darrieus", La Nature, Vol.57, No. 2823, pp. 547-554, 1929.
60. G. MAGNUS, "On the deviation of projectiles; and a remarkable phenomenon of rotating bodies", From the memoirs of the Royal Academy, Berlin, 1852, Taylors Scientific Memoirs, Vol.7, pp. 210-31, 1966.
61. F. WILHOFT, "Industrial applications of the Flettner rotor", Mechanical Engineering, Vol.49, No.3, pp. 249-55, 1927.
62. P. CRIMI, "Performance assessment of the Flettner wind-turbine", Journal of Energy, Vol.4, No.6, pp. 281-284, 1980.

REFERENCES

63. S.J. SAVONIUS, "The S-rotor and its applications", Mechanical Engineering, Vol.53, No.5, pp. 333-338, 1931.
64. J.D. MADARASZ, "wind engine", US Patent No. 1,791,731 , 1931.
65. D.H. WHITFORD and J.E. MINARDI, "Utility-sized Madaras wind plants", Journal of Ambient Energy, Vol.2, No.1, pp. 3-21, 1981.
66. N.N. MILLAR, "A review of United Kingdom wind power", Journal of Ambient Energy, Vol. 3, No. 1, pp. 35-46, 1982.
67. P.J. MUSGROVE, "The economics of existing wind-turbines in the size range 10 to 100 metre diameter" Proceedings of the Fifth British Wind Energy Association Workshop, Reading University, March, 1983, To be published by Cambridge University Press, 1984.
68. M.M. SHERMAN, "Practical applications of wind powered water pumps", Proceedings of the Workshop on Biogas and other Rural Energy Sources, Energy Resources and Development Series, United Nations, New York, pp. 90-107, 1979.
69. P.N. SHANKAR, "The effects of geometry and Reynolds number on Savonius-type rotors", Technical Memorandum AE-TM-3-76, National Aeronautical Laboratory, Bangalore, India, 1976.
70. ANONYMOUS, "Experimenting with a novel sail-wing rotor", Windpump News, Vol. 1, No. 2, TATA Energy Research Institute, Bombay, p. 2, 1982.
71. P.S. REVELL and K.W. EVERITT, Sail-wing Darrieus rotors, Wind Engineering, Vol. 4, No. 1, pp. 11-31, 1980.
72. S.K. TEWARI, "Economics of wind energy use for irrigation in India", Science, Vol. 202, pp. 481-486, 1978.
73. D. HAYES, "Energy for development: third world options", Worldwatch Institute, Washington DC, 1977.
74. P. FRAENKEL, "Wind pumps for development", Windirections, pp. 10-11, September, 1983
75. D.J. HILTON, "Some wind power developments in Kenya" pp. X75-X76, International Symposium on Wind Energy Systems, Cambridge, BHRA Fluid Engineering, Cranfield, UK, 1976.
76. M.M. SHERMAN, "The sail windmill and its adaption for use in rural India", Wind Energy Conversion System Workshop, Washington DC, pp. 75-79, 1973.
77. R. RAMAKUMAR, "Harnessing wind power in developing countries", pp. 966-973, Tenth Intersociety Energy Conversion Conference, Delaware University, Newark, USA, 1975.
78. F. ROBERTS, "Energy accounting of alternative energy sources", Applied Energy, Vol. 6, No. 1, pp. 1-20, 1980.

REFERENCES

79. "Report of the technical panel on wind energy", Second Session, A/CONF/100/PC/24, United Nations Conference on New and Renewable Sources of Energy, United Nations, New York, 1981.
80. F. MOORE LAPPE, J. COLLINS and D. KINLEY, "Aid as obstacle", Institute for Food and Development Policy, San Francisco, U.S.A., 1980.
81. Commission on the Church's Participation in Development, "On appropriate technology 2", Document No. 16, World Council of Churches, Geneva, 1979.
82. E.E.C. "Memorandum on the Community's development policy", The Courier, No. 76, pp. 48-74, 1982.
83. J. van den BERG, "Village Technology: lightening the woman's burden", The Courier, No. 62, pp. 90-92, 1980.
84. A. CLAUSEN, "Annual report on development", The World Bank, 1982.
85. A. MATHESON, "Third World is bitter after energy summit", The Observer, 23rd August, 1981.
86. CHRISTIAN AID "The aid business", Christian Aid, London, 1979.
87. J. TENDLER, "Rural electrification: linkages and justifications", AID Programs Evaluation, Discussion Paper No. 3, Studies Division, Office of Evaluation, Agency for International Development, Washington D.C., U.S.A, 1979.
88. V. MUBAYI, T. LE and J. LEE, "Irrigation in less developed countries", National Center for Analysis of Energy Systems, Brookhaven National Laboratory, New York, 1979.
89. A. WYATT, "Report surveys potential for wind energy in Africa", V.I.T.A. News, pp. 17-18, July, 1981.
90. D. WHYTE (ed), "Third World Development", Grosvenor Press, London, pp. 255-296, 1982.
91. W.J.M. RANKINE, "On the mechanical principles of the action of propellers", Transactions of the Institute of Naval Architects, Vol. 6, pp. 13-39, 1865.
92. R.E. FROUDE, "On the part played in propulsion by differences in fluid pressure", Transactions of the Institute of Naval Architects, Vol. 30, pp. 390-405, 1899.
93. A. BETZ, Zeitshur fur Flugtechnik und Motorl. Vol. 11, p. 105, 1920.
94. W. FROUDE, "On the elementary relation between pitch slip and propulsive efficiency", Transactions of the Institute of Naval Architects, Vol. 19, pp. 47-57, 1878.

REFERENCES

95. S. DRZWIECKI, "Sur une methode pour la determination des elements mechaniques des propulseurs helicoidaux" Comptes rendus de l'Academie de Sciences, Paris, Vol. 114, pp. 810-822, 1892.
96. F.W. LANCHESTER, "Aerodynamics", Constable and Company Limited, London, 1907.
97. FLAMM, Die Schiffschraube, Berlin, 1909.
98. N.E. JOUKOWSKI, "Theorie tourbillonnaire de l'helice propulsive", Gauthier-Villars, Paris, 1929.
99. A. BETZ, "Schraubenpropeller mit geringsten energieverlust" Gottinger Nachrichten, Mathematisch-physikalische Klasse, pp. 193-213, 1919.
100. L. PRANDTL, "Tragflugeltheorie" Gottingen Nachrichten, Mathematische-physikalische Klasse, pp. 107-137, 1919.
101. S. GOLDSTEIN, "On the vortex theory of screw propellers", Proc. Royal Society, A123, pp. 440-465, London, 1929.
102. W.F. DURAND (Editor), "Aerodynamic theory", Vol. IV, Julius Springer, Berlin, 1934.
103. A. BETZ, Windmills in the light of modern research, NACA Technical Memorandum, No. 474, Translated from Die Naturwissenschaften, XV (46), 1927.
104. J. BEURSKENS, M. HOUET, and P. van der VARST, "Wind energy", diktaat No. 3323, Eindhoven University of Technology, Eindhoven, The Netherlands, April 1974.
105. W.A.M. JANSEN, "Horizontal-axis fast running wind-turbines for developing countries", Steering committee for Wind energy in Developing countries, Amersfoort, the Netherlands, June 1976.
106. K. VOELZ, "Profil und auftrieb eines segels", Z.A.M.M., Vol. 30, pp. 301-317, 1950.
107. V. CISOTTI, "Moto con scia di un profilo flessibile, Nota I and II", Rendiconti della reale, Accad, Nat. dei Lincei, Vol. 15, pp. 166-173, and pp. 253-257, 1932.
108. B. THWAITES, "Aerodynamic theory of sails", Proceedings of the Royal Society, Series A, Vol. 261, pp. 402-422, 1961
109. J.N. NIELSEN, "Theory of flexible aerodynamic surfaces", Journal of Applied Mechanics, Vol. 30, pp. 435-442, 1963,
110. E.P. WARNER and S. OBER, "The aerodynamics of yacht sails", Transactions of the Society of Naval Architects, Vol. 33, pp. 207-232, 1925.
111. J.P. DUGAN, "A free-streamline model of the two-dimensional sail", Journal of Fluid Mechanics, Vol. 42, Pt. 3, pp. 433-446, 1970.

REFERENCES

112. J.W. BUGLER, "On the application of potential flow theory to the aerodynamics of sails", Thesis, College of Aeronautics, Cranfield Institute of Technology, Bedford, U.K., 1957.
113. L.G. CHAMBERS, "A variational formulation of the Thwaites sail equation", Quarterly Journal of Applied Mathematics", Vol. 9, pp. 221-231, 1966.
114. R. BARAKAT, "Incompressible flow around porous two-dimensional sails and wings", Journal of Mathematics and Physics, Vol. 47, pp. 327-349, 1968.
115. A.Q. CHAPLEO, "A review of two-dimensional sails", S.U.Y.R. report No. 23, Southampton University, April, 1968.
116. J.O. MYALL and S.A. BERGER, "Recent progress in the analytical study of sails", Proceedings, 2nd AIAA Symposium on Aero/hydro-nautics of sails, Los Angeles, USA, 1969.
117. E.O. TUCK and M. HASELGROVE, "An extension of two-dimensional sail theory", Journal of Ship Research, Vol. 16, pp. 148-152, 1972.
118. J.M. VANDEN-BROEK, "Non-linear two-dimensional sail theory", The Physics of Fluids, Vol. 25, No. 3, pp. 420-423, 1982.
119. T.E. SWEENEY "Exploratory sail-wing research at Princeton" Report No. 578, Department of Aero. Eng., Princeton University, USA, 1961.
120. J. ROBERT and B.G. NEWMAN, "The lift and drag on a sail aerofoil", Wind Engineering, Vol. 3, No. 1, pp. 1-22, 1979.
121. S.K. TEWARI, "Economics of wind energy use for irrigation in India" Science, Vol. 202, No. 3, pp. 481-486.
122. G.M. LILLEY and W.J. RAINBIRD, "A preliminary report on the design and performance of ducted windmills", Technical Report C/T119, British Electrical and Allied Industries Research Association, Leatherhead, England, 1957.
123. R.A. OMAN and K.M. FOREMAN, "Advantages of the diffuser augmented wind-turbine" Proceedings, Wind Energy Conversion Systems Workshop, Washington D.C. USA, pp. 103-106, 1973.
124. O. IGRA, "Shrouds for aerogenerators" AIAA Paper No. 76/181, 1976.
125. O. IGRA, "The shrouded aerogenerator" Energy, Vol. 2, pp. 429-439, 1977.
126. O. IGRA, "Research and development for shrouded wind-turbines", Energy Conservation and Management, Vol. 21, No. 1, pp. 13-48, 1981.

REFERENCES

127. O. IGRA, "Israeli work on aerogenerator shrouds", Wind Workshop 2, The Mitre Corporation, Washington DC, pp. 149-155, 1975.
128. D.L. SENAGUPTA and T.B.A. SENIOR, "Electromagnetic interference to television reception caused by horizontal-axis windmills", IEE proceedings, (USA), Vol. 68, pp. 1-20, 1980.
129. Th. van HOLTEN, "Performance analysis of a windmill with increased power due to tipvane diffusion of the airstream", Memorandum M-224, Technische Hogeschool, Delft, The Netherlands, 1974.
130. R.E. WILSON, "The effect of hub-fairings on wind-turbine rotor performance", Journal of Fluids Engineering, Vol. 100, No. 1, pp. 120-122, 1978.
131. R.T. GRIFFITHS, "Centre-body effects on horizontal-axis wind-turbines", Applied Energy, Vol. 13, pp. 183-94, 1983.
132. NEW YORK UNIVERSITY, COLLEGE OF ENGINEERING, "Wind-turbine project WPB 144", Engineering Research Division, New York, War Production Board, Washington DC, 1946.
133. WATSON-MARLOW LIMITED, Falmouth, Cornwall, TR11 4RU, UK, 1980.
134. ANONYMOUS, "New twist on peristaltic pumping" Chartered Mechanical Engineer, p. 2, December, 1982.
135. T.J.M. ROBERTSON, Private communication, January, 1984.
136. R. RAYMENT, "Wind energy in the UK" Building Services Engineer, Vol. 44, No. 3, pp. 36-69, 1978.

APPENDICES

APPENDIX A

SAIL-TYPE WIND-TURBINES: A REVIEW AND ANNOTATED BIBLIOGRAPHY

(This is taken from *Applied Energy*, Volume 10, pages 273 to 286, 1982)

SAIL-TYPE WIND-TURBINES: A REVIEW AND ANNOTATED BIBLIOGRAPHY

P. D. FLEMING and S. D. PROBERT

*School of Mechanical Engineering, Cranfield Institute of Technology,
Cranfield, Bedford MK43 0AL, Great Britain*

PREFACE

This compilation of abstracts should provide a comprehensive introduction for those engineers wishing rapidly to gain an understanding of the design, construction and performance of windwheels with flexible sails. Such turbines are used for various purposes throughout the world. However, the references which have been selected and presented in this bibliography will inevitably—although unintentionally—reflect the compilers' research interest—namely Cretan-type windwheels. Also, the presented abstracts are not usually those of the original authors, but rather the compilers' interpretations of the contents of each paper.

The abstracts are classified into nine groups, the first six of which are concerned with the history, development and use of sail-type wind-turbines. The seventh group makes reference to possible refinements to low speed, horizontal-axis, Cretan-type turbines whereas the eighth section outlines vertical-axis sail turbines. The final group introduces two books, which deal primarily with small-scale harnessing of wind power.

I. HISTORY OF SAIL WINDMILLS

The first paper in this section concerns windmills in general, the remaining two deal with their evolvement on the island of Crete.

1.1. H. P. VOWELS, An inquiry into the origins of the windmill, *Transactions of the Newcomen Society*, 11 (1930), pp. 1-14.

Western horizontal-axis windmills probably evolved from the Persian vertical-axis type, despite differences in structure and the great distances separating their occurrence. The 11th century Domesday survey refers to five to six thousand mills

in England and Wales—but wind and water mills are not distinguished, and Vowels suggests that the majority were water mills, plus a few cattle mills. Greek, Latin, Italian, French and German translations of the *Pneumatica of Heron of Alexandria* were examined in an attempt to understand Heron's 'Windmill'.

Windmills were almost certainly known in Persia by the 10th century, AD (possibly by as early as the 7th century) and probably evolved from Graeco-Roman inventions. The author suggests that the design of the Greek windmill travelled to Persia (in the early Christian era), then naturally found its way across Russia to Europe, probably to Holland, in the 10th to 11th centuries, AD.

1.2. N. G. CALVERT, Windpower in Eastern Crete, *Transactions of the Newcomen Society*, XLIV (1972), pp. 137-44.

The described Aegean windwheel uses six to twelve triangular canvas sails and incorporates aerodynamic and structural features similar to the modern sailing yacht. The machines on Crete are small by European standards and appear to have their sails set for rotational speeds of around 25 rpm. The wind pumps of eastern Crete, their performance and the reasons for their decline in popularity are discussed. Those Cretan windmills, which were mentioned in early English language publications, are outlined.

1.3. N. G. CALVERT, The mono-kairos windmills of Lasithi, *Annual, British School at Athens*, 70(51) (1975), pp. 51-7.

Nineteenth and early twentieth century English language publications are examined for various references to windmills. Most of the windmills on Crete are fixed in the direction facing the prevailing wind. These mono-kairos (i.e. single weather) windmills occur in groups, whereas the circular tower mills (in which the cap can rotate to face the wind) are generally isolated. Comparison is made in this paper with the European windmill and the building and milling mechanisms are described, in particular the wooden gear-wheel construction is shown.

2. CRETAN-TYPE WIND-TURBINES

The advantages of the Cretan windwheel over other types of wind-rotor are considered in this section.

2.1. S. B. WATT, The Cretan windwheel as a power source, *Appropriate Technology*, 2(3) (1975), pp. 4-5.

The Cretan sail windwheel is still widely used in many countries, indicating its persisting—and now probably increasing—economic value. Its useful power harnessing operation in low wind speeds, the ability of the sails to shape themselves to the wind, as well as the simplicity of construction and maintenance, are said to be its major advantages. A typical installation for water pumping is shown and a comparison with the multi-blade windwheel is given. Efficiencies of over 30% are

possible but trial-and-error methods still need to be used for obtaining the best rigging and optimal settings of the sails because pertinent information is not recorded in the readily available literature.

2.2. M. M. SHERMAN, *6000 hand-crafted sailwing windmills of Lassithiou, Greece, and their relevance to windmill development in rural India, Appropriate technologies for semi-arid areas: Wind and solar energy for water supply*, German Foundation for International Development, 1975, pp. 89-93.

The author visited Lassithiou, Crete, in order to ascertain the reasons for the widespread and persistent use of the Cretan-type wind-turbines there, as well as to determine if any of the design details could be incorporated (and so improve) water-pumping windwheels for rural India. The success of Cretan windmill design is attributed to the use of inexpensive and lightweight cloth sails and local hand-craftmanship in construction. As a result of this investigation, an improved wind-turbine design was developed for use in rural India.

2.3. N. G. CALVERT, *The Cretan windmill*, National Centre for Alternative Technology, Machynlleth, Wales, 1977.

A brief history of the Cretan type of windwheel is outlined and a general description given (see also 'Do-it-yourself' Cretan windmill, section 3.3).

The Cretan windwheel, designed and built at the National Centre for Alternative Technology, is described.

2.4. M. T. KANAKI and S. D. PROBERT, Cretan windmills, *Applied Energy*, 5(3) (1979), pp. 215-22.

An historical perspective is given for the Cretan windmill, the design of which incorporates a near-horizontal shaft with radial spars carrying triangular canvas sails. The tip-speed ratio is defined, the site selection procedure outlined and elementary wind power theory given. Cretan-type windmills are particularly suitable for harnessing wind energy at low wind speeds (i.e. $< 5 \text{ m s}^{-1}$) and are easily constructed. They offer a potentially useful source of available power for most developing countries.

3. CONSTRUCTION

Practical details are outlined for commissioned Cretan-type windwheels and their supporting structures.

3.1. A. B. BIRD, *Windmill tower in reinforced brickwork*, Structural Clay Products Ltd., Potters Bar, Great Britain, 1976.

A structural analysis is presented of a Cretan sailwing windmill on a brick tower at Rotherhithe, Great Britain. The advantages of brickwork are said to be structural rigidity, ease of construction, durability, good appearance and design flexibility.

This report also contains constructional details for a 40 ft diameter Cretan sail windwheel. When used for pumping water, it had a starting speed of 3 to 4 mph and produced a maximum of 13 horse power in 25 to 30 mph winds.

3.2. M. M. SHERMAN, A water-pumping windmill that works, *Journal of The New Alchemists*, 2 (1973), pp. 21-7.

Constructional details are provided for an 18 ft diameter sailing rotor, mounted on a 26 ft tower. The windmill consists of three cloth sails attached to three tubular steel masts fastened to a triangular plywood hub. Pumping trials showed a yield of 250 gallons per hour of water, raised 14 ft, in a 6 mph wind, but the pump was considerably undersized for the wind-turbine.

3.3. *Do-it-yourself plan 5: Sail windmill (Cretan), Parts 1 and 2*, National Centre for Alternative Technology, Machynlleth, Wales. (Part 1, 1975; Part 2, 1977).

A 12 ft diameter Cretan-type sail wind-turbine is described. It can be used as a prime mover for motivating a lathe and grindstone, or for pumping water. With a step-up gearing of about 1:50 it may be employed for electrical generation of up to 700 W. Part 1 deals with the tower structure and the windwheel as a prime mover. Part 2 includes details of the gearbox, turntable and electrical generator.

3.4. M. M. SHERMAN, The design and construction of low-cost wind-powered water-pumping systems, *Proceedings of the Meeting of the Expert Working Group on the Use of Solar and Wind Energy*, Energy Resources Development Series No. 16, United Nations, New York, 1976, pp. 76-104.

Data concerning the design of water-pumping wind-turbines, suitable for construction with low cost, indigenous materials and locally available skills, are presented. Technical information about such horizontal- and vertical-axis windwheels for driving various reciprocating or rotary motion pumps are described, along with three novel designs for water pumping. An example of the design procedure associated with a low cost, Asian, hybrid water-pumping wind-turbine is outlined.

3.5. N. VAN DE VEN, *Construction manual for a Cretan windmill*, Steering Committee for Wind Energy in Developing Countries, Amersfoort, The Netherlands, 1977.

The designs described here, for a wood-work lathe, a piston pump and a slow running windmill, are of an intermediate technology character. The aim has been to make designs which can be entirely constructed from materials which are generally available, e.g. logs, rugged sawn wood and piping. Connections have been made using wood screws (sometimes telephone pole bolts) and pieces of threaded bar (commercially obtainable in lengths of 1 m: M8, M10, etc). When these materials are not available, use can be made of mortise joints, possibly in combination with glued and rope tied joints. However, the latter type makes higher demands on both the tools available and the skills of the constructors. Only manual

tools (e.g. chisels, handsaws, hand-drills, hammers, etc.) were used to assemble the prototypes of the equipment.

3.6. R. D. MANN, *How to build a 'Cretan sail' wind pump*, Intermediate Technology Publications, London, 1979.

A Cretan sail wind pump, constructed in Gambia and based upon the 'Omo' wind pump in Ethiopia (see P. FRAENKEL; *Food from windmills*, section 5.2) is described. As the winds are less intense in Gambia, the design had to be adapted accordingly and was also improved. Meteorological and hydrological considerations are outlined and constructional details given. The final result was a successful wind pump that delivered nearly twice as much water as the original 'Omo' design.

4. PERFORMANCE CHARACTERISTICS

The behaviours of existing Cretan type windwheels are indicated in the references of this section.

4.1. TH. A. H. DEKKER, *Performance characteristics of some sail and steelbladed wind rotors*, Steering Committee for Wind Energy in Developing Countries, Amersfoort, The Netherlands, 1977.

Experiments were carried out on Cretan, rectangular-sail, sail-wing, steelplate and sail trouser-type rotors and the results are presented graphically as torques and power coefficients against tip-speed ratios. The parameters investigated included mast thickness, sail material, sail coating and the type of sail attachment. The results showed favourable characteristics for rectangular, Cretan and steel-plate type rotors, but tests on sail-wing and sail-trouser rotors were disappointing because the performance was over-sensitive to likely constructional peculiarities.

4.2. N. G. CALVERT, The characteristics of a sail mill, *Journal of Industrial Aerodynamics*, 3(1) (1978), pp. 79-84.

The Cretan type windwheel is described. Field tests on a 4 m diameter sail mill showed that the optimal performance occurred at low wind speeds. An experimental, 1.5 m diameter, windwheel was constructed and performance data are presented. The experimental parameters included the number of sails, the solidity ratio, the sail angle of incidence to the wind and the stiffness of the sails. A high starting torque (with moderate ability to harness power) is said to follow from the use of large, loosely sheeted sails.

4.3. P. D. FLEMING and S. D. PROBERT, Design and performance of a small, shrouded, Cretan windwheel, *Applied Energy*, 10(2) (1982), pp. 121-139.

A brief history and description of Cretan windwheels is given and the major attributes of flexible sails are described. The advantages of utilising a shroud and the use of the windwheel to drive a peristaltic pump are discussed. Data are presented

for a shrouded Cretan windwheel of 0.64 m diameter, based upon a cycle wheel, and designed to operate in low speed wind regimes ($< 5 \text{ m s}^{-1}$). The study shows that nine loosely sheeted sails produce a maximum power of 14 W at an air speed at entry to the rotor of 5 m s^{-1} (corresponding to a free wind speed of less than 3.5 m s^{-1}).

Two possible applications for a shrouded Cretan windwheel are described—(i) for irrigation and land drainage in under-developed countries and (ii) for stimulating a peristaltic pump which acts as a gravitational boost to convey solar-heated anti-freeze liquid around a low height, domestic central-heating circuit.

5. UNDER-DEVELOPED NATIONS

The considerable potential for the use of Cretan-type sail windwheels in the third world is discussed in this section.

5.1. M. M. SHERMAN, The sail-wing windmill and its adaption for use in rural India, *Wind Energy Conversion Systems—Workshop Proceedings*, Washington DC, 1973, pp. 75–79.

A 25 ft diameter sail-wing wind-turbine was built in 1973 in a small village near Madurai, Tamilnadu State, India. This wind-turbine was the result of design research conducted in the USA (at the New Alchemy Institute-East) and in India (at the Indian Institute of Agricultural Research and the Wind Power Division of the National Aeronautical Laboratory). The wind-turbine is used mainly in light winds during the dry winter months for irrigating small fields, watering dairy cattle and supplying water for domestic use.

5.2. P. FRAENKEL, *Food from windmills*, Intermediate Technology Publications, London, 1975.

This pamphlet describes studies carried out to improve and evaluate a series of wind-turbines developed for irrigating (with river water) small plots of land on the banks of the Omo river in Ethiopia. Various 11, 14 and 16 ft diameter 'Cretan sail' and Savonius-type wind-rotors were constructed from local materials using basic skills. A 'Dempster' multi-vane wind pump, imported from the USA, was also tested. The sail windwheels proved to be more acceptable and were capable of pumping 1300 gallons of water per hour against a 9 ft static head: design and constructional details are presented. Meteorological conditions, data collection, water distribution and crops are also discussed.

5.3. M. M. SHERMAN, Development of wind energy utilisation in Asia and the Pacific, *Proceedings of the Meeting of the Expert Working Group on the Use of Solar and Wind Energy*, Energy Resources Development Series, No. 16, United Nations, New York, 1976, pp. 61–75.

Means of evaluating local energy needs and wind data are described. The status of wind-turbines for water pumping is outlined, with reference both to (i) manually

produced mechanical drive wind pumps, including the Cretan, Chinese and Thai wind-turbines and (ii) industrially-produced mechanical wind pumps. Two wind-turbines for other uses (e.g. grinding) are also described. The selection and matching of traditional components for the design of hybrid wind-turbines are classified.

5.4. S. K. TEWARI, An evaluation of the strategy of low-cost, horizontal-axis windmills, *Sun: Mankind's future source of energy, Proceedings of the International Solar Energy Congress, New Delhi, India, Vol. 3, 1978, pp. 16-21.*

An attempt is made to assess the relative cost-effectiveness of three wind-turbine designs, with efficiencies exceeding 5 %. Two of the versions are low cost technology wind-turbines constructed from locally available materials (the 'Madurai' and 'Cretan'). The third is an all-metal, factory produced wind-turbine. The economics of these are compared.

5.5. R. A. WILLEM, A wind energy review: Wind machines for agricultural and rural applications, *Caribbean Consultation on Energy and Agriculture (Bilingual edition), Instituto superior de agricultura, Dominican Republic, 1980, pp. 408-17.*

Savonius, multi-vane and Cretan low technology wind-rotors with high solidity ratios—and hence high developed torques—are discussed. These are best suited for pumping groundwater. The Cretan-sail wind-pump is said to be the most appropriate for developing countries, as it can be manufactured and maintained with simple tools and technology at relatively low cost. The author concentrates upon wind-rotors for water-pumping applications, as wind-electric systems are less effective and too expensive, at present, for widespread use in developing countries. Also, neither the intermittency, nor the low energy density of the wind usually present serious drawbacks for irrigation applications. The introduction of wind-pumps into rural areas of developing countries is said to have the additional benefits of creating small industries, where unemployment tends to be the greatest. The use of rotor centre-bodies could further improve such wind-rotor performances.

6. IRRIGATION

Cretan-type windwheels are frequently used as power sources for irrigation.

6.1. M. M. SHERMAN, *An interim report: The design and construction of an appropriate water-pumping windmill for Indian agriculture. Appropriate technologies for semi-arid areas: Wind and solar energy for water supply*, German Foundation for International Development, 1975, pp. 95-111.

Design criteria for a water-pumping wind-turbine are outlined. The 25 ft diameter windwheel, with six sails in the classical Cretan configuration, was an adaption of the traditional Greek sail-wing. Descriptions of the windwheel and pump are given, along with the control mechanisms, power equations and suggestions on implementation.

6.2. S. K. TEWARI, Economics of wind energy use for irrigation in India, *Science*, 202(3) (1978), pp. 481-6.

The harnessing of energy by Cretan and Madurai-type wind-turbines, operating under low wind velocities, is predicted to be economic for irrigating small farms from open wells. The financial attractiveness of the system would improve if the irrigation were practised all the year round, even in the hot summer season. The given data are expected to be valid for the 10 % most windy of locations identified from available wind speed records. Government inducement policies, analogous to those applied for rural electrification, will probably be needed to support research and development efforts to optimise the designs of wind-turbines and promote their use in rural areas.

6.3. M. M. SHERMAN, Practical applications of wind-powered water pumps, *Proceedings of the Workshop on Biogas and Other Rural Energy Resources, and the Roving Seminar on Rural Energy Development*, Energy Resources Development Series No. 19, United Nations, New York, 1979, pp. 90-107.

Technical performance and economic characteristics of a full range of wind-powered water pumps (WPWP's) are summarised in tabular form and brief evaluations are made of some of the inter-relationships. The survey of the variables encountered in the practical application of WPWP's is intended to assist in the design, selection and evaluation of future WPWP systems. Water source, water use, local wind conditions and availability of labour, capital and materials are seen as the major determinants in design selection.

This report may be regarded as a supplement to (i) Development of wind energy utilisation in Asia and the Pacific (see section 5.3) and (ii) The design and construction of low-cost wind-powered water pumping systems (see section 3.4).

6.4. S. K. TEWARI, N. INGAIAH, D. V. V. SUBRAMANYAM and A. C. SCAMRAJ, Horizontal-axis sail-windmill for use in irrigation, *Proceedings of Indian Academy of Science, Section C*, Vol. 2, Part 1, 1979, pp. 107-16.

Some basic considerations are described in the design and development of a horizontal-axis wind-turbine intended primarily for irrigation in small farms from shallow open wells. It has six triangular sails sweeping a circle of 10 m diameter and is an adaptation from Greek sail windwheels. For the construction of this wind-turbine, efforts were made to use materials and parts readily available in the local hardware market, except for the gearboxes. Preliminary performance tests have indicated a pumping rate of 6000-11 000 litres/h over a head of 6.85 m in wind speeds of 10-16 km/h.

7. POTENTIAL REFINEMENTS TO INCREASE WINDWHEEL POWER OUTPUTS

The possible uses of shrouds, centre-bodies and tip-fins to augment windwheel performance are discussed in this section.

7.1. Shrouds

Substantial power enhancement advantages for a wind-rotor can be realised by the presence of a shroud. The first paper describes a preliminary study carried out in the 1950's, the remaining two papers outline continuing research programmes in Israel and the United States. There are many papers by American and Israeli authors, the two references given here describe their more recent work.

7.1.1. G. M. LILLEY and W. J. RAINBIRD, *A preliminary report on the design and performance of ducted windmills*, College of Aeronautics Report 102, Cranfield Institute of Technology, Great Britain, 1956. Also available as: Technical Report C/T 119 British Electrical and Allied Industries Research Association, Leatherhead, Great Britain, 1957.

A study of the theoretical gain in power output obtained by fully ducting a wind-turbine is presented. The design of the shroud, together with its effects on the overall wind-turbine performance, are discussed. The greater output is due to (i) a reduction in the tip losses and (ii) the effect of a gain in axial velocity through the wind-turbine resulting from increased diffusion of the slipstream.

7.1.2. K. M. FOREMAN and B. L. GILBERT, Technical development of the diffuser-augmented wind turbine (DAWT) concept, *Wind Engineering*, 3(3) (1979), pp. 153-66.

The theory of the DAWT is presented and recent experimental data are compared with measurements from preceding tests. The objective of the DAWT research programme was to increase the energy extracted from the wind by increasing the mass flow through the rotor, while minimising the costs of the additional system. A power augmentation ratio of 3.4—compared with an ideal conventional wind rotor—is obtained with a 0.46 m diameter turbine and further refinements are expected to raise this factor to between 6 and 8.

7.1.3. O. IGRA, Preliminary results from the shrouded wind-turbine pilot plant, *Journal of Energy*, 4(4) (1980), pp. 190-2.

This paper describes the first three months of field tests on a 3 m diameter, shrouded wind-turbine. The shrouded assembly withstood wind speeds of up to 95 km h^{-1} and produced an average electrical power output of 0.66 kW. This corresponded to a power augmentation of two: that is, twice as much power was harnessed compared with an ideal 3 m diameter unshrouded rotor under the same free-stream conditions. References are given concerning previous work and the design and construction of this particular pilot plant.

7.2. Centre-body

Properly shaped centre-bodies could augment wind-rotor performances by diverting the wind stream from the rotor hub area, where it is not effectively harnessed, towards the rotor circumference; that is, onto the sails rather than the hub.

The following two papers describe research on centre-bodies, the first concentrating solely on the spinner (or hub fairing) and the second dealing with the whole centre-body (i.e. spinner plus after-body).

7.2.1. R. E. WILSON, The effect of hub fairings on wind-turbine rotor performance, *Journal of Fluid Engineering*, **100**(1) (1978), pp. 120-1.

This paper discusses the effect of hub fairings or spinners on the performance of wind-turbine rotors. Diagrams, mathematical analyses and the results of previous tests are presented.

7.2.2. T. E. SWEENEY, W. B. NIXON, M. D. MAUGHMER and R. BLAHA, *Sailwing windmill characteristics and related topics*, Department of Aerospace and Mechanical Sciences, Princeton University, Report No. 1240, 1975.

In Appendix 2 to this paper, R. Blaha presents a three-dimensional potential flow model of a centre-body. For centre-body diameters up to 40 % of the rotor swept area, the total kinetic energy of the stream passing through the rotor is increased. A 20 % power rise is observed due to the presence of the centre-body. The experiments concern small-scale models and the results are not readily extrapolated quantitatively for large-scale systems.

7.3. Tip-fins

The use of small tip-fins to reduce trailing vortex drag could improve the performances of Cretan-type windwheels. Reductions in drag of up to 27 % have been obtained for aircraft wings and, by placing the fins at the circumference of wind-rotors, appreciable reductions in vortex drag and increases in air mass flow through the rotor, should be possible. The first two and the last references in the following section deal with wind-turbine tip-fins, whereas the remaining two references refer specifically to aircraft wings.

7.3.1. G. A. M. VAN KUIK, *Preliminary design of a wind tunnel model of a tip-vane wind-turbine*, Department of Aerospace Engineering, Memorandum No. M-270, University of Technology, Delft, The Netherlands, 1977.

This report describes the preliminary studies on the design of a 'tip-vane wind-turbine' test model. The research model consists of a rod (analogous to a two-bladed wind turbine), to each end of which a tip-vane is attached. Tip-vane adjustment is possible in three directions (incidence, tilt and sweep) and the model was tested in a wind tunnel and in water using a towing tank. A general arrangement of the model is given, along with details of the measuring equipment and the structural aspects of the test rig, both in air and in water.

7.3.2. Th. VAN HOLTEN, Tip-vane research at the Delft University of Technology, *Proc. 2nd International Symposium on Wind Energy Systems*, BHRA Fluid Engineering, Cranfield, Bedford, Vol. 1, Paper No. F2, 1978, pp. 13-24.

This paper outlines the first results of the experimental work carried out to verify the tip-vane concept. These showed mass flow augmentation factors of four to five. Flow visualisation of the diffuser effect for the tip-vanes mounted on a rod are given, no attempt being made to study the complete turbine tip-vane system. Vortex patterns, boundary layer anomalies and preliminary drag measurements are described. By careful design of the tip-vanes to minimise drag, improvements in power output by a factor of two are possible.

7.3.3. J. J. SPILLMAN, The use of wing tip sails* to reduce vortex drag, *Aeronautical Journal*, **82** (1978), pp. 387-95.

Results are examined for wind-tunnel studies of the flow behind the tip of an unswept wing of moderate aspect ratio. Effects of wing-tip fins on the drag of an aircraft are analysed, wind-tunnel tests on fins mounted from tip tanks are discussed and flight tests with fins on tip tanks are described, along with wind tunnel tests on a model aircraft with plain wing-tips. The effectiveness of fins in reducing the lift-dependent drag factor is evaluated. It is shown that fins fitted to the wing-tips of an aircraft can reduce its lift-dependent drag by up to 30 %. Three or four fins per wing-tip, each having a span of 0.25 of the wing-tip chord and a root chord of 16 % of that of the wing-tip, appear to give the greatest vortex drag reduction when fitted, almost horizontally, outboard of the rear half of the wing tip.

7.3.4. J. J. SPILLMAN, H. Y. RATCLIFFE and A. MCVITIE, Flight experiments to evaluate the effect of wing tip sails* on fuel consumption and handling characteristics, *Aeronautical Journal*, **83** (1979), pp. 279-81.

The results of experiments performed with a Paris MS 760 aircraft modified with wing tip-fins to reduce vortex drag are presented. Specifications and test procedures are described and it is shown that the fuel flow-rate and engine speed are uniquely linked. Attention is given to handling characteristics such as the aircraft's ability to take-off at up to 10 knots slower than without wing-tip fins. It is concluded that the total drag, at lift coefficients above 0.22, is reduced because the lift-dependent drag is reduced by 27 %. The fuel saving is about 4.5 % at a typical lift coefficient of 0.35, rising to almost 11 % at a lift coefficient of 0.8.

7.3.5. TH. VAN HOLTEN, Concentrator systems for wind energy, with emphasis on tip-vanes, *Wind Engineering*, **5**(1) (1981), pp. 29-45.

The author suggests that research effort is needed to develop cost-effective concentrator techniques for wind-turbines. A general aerodynamic theory for wind energy concentrators is described and various types of augmentors discussed, with specific emphasis on tip-vanes. The validity of the theory was verified for the tip-vane concept using wind-tunnel, towing-tank and flow visualisation facilities.

* Such sails are called 'fins' in this bibliography to avoid confusion with the flapping sails, of say, a Cretan windmill.

It is expected that considerable reductions in the cost of harnessing wind energy may be achieved by the application of concentrator techniques.

8. VERTICAL-AXIS SAIL WINDWHEELS

The advantage of this system is that the harnessed power is more readily transferred to ground level. It is non-directional and so self-starting. Thus it has considerable potential.

8.1. J. S. CAMPBELL, The Campbell Chinese type windmill, *Sun: Mankind's future source of energy, Proceedings of the International Solar Energy Congress*, New Delhi, India, Vol. 3, 1978, pp. 1790-5.

A new vertical-axis wind-turbine which uses an old basic operating principle---that of the Chinese windmills---has been developed. It has been engineered aiming principally at low costs and the ability to utilise a wide range of wind velocities including lower velocity winds. A device for stopping the windwheel operation, or rotation, while the wind is blowing, is included. This new wind-turbine is said to possess the following distinctive advantages: (1) low total weight; (2) no unusual size limitation; (3) no strengthening limitation; (4) high starting torque; (5) satisfactory efficiency; (6) ability to utilise lower velocity winds; (7) intercepted wind area is rectangular; (8) relatively low sail-velocities; (9) similar type equipment can be used in flowing water such as tides and rivers and (10) low production costs per rated kilowatt.

8.2. B. G. NEWMAN and T. M. NGABO, The design and testing of a vertical-axis wind turbine using sails, *Energy Conversion*, 18(3) (1978), pp. 141-54.

A vertical-axis wind-turbine using sails rather than solid blades has been designed and tested in a 15 ft diameter wind-tunnel. The turbine has a relatively high solidity, three blades and an operating range of tip speed ratios from zero to about 2.5. Two types of sail have been tested---a double sail consisting of two layers of cloth wrapped round a circular leading edge dowel, and a jib sail consisting of a single layer of cloth with the leading edge held by a taut wire. The measured power outputs are about half those of a turbine with solid aerofoil blades running at tip speed ratios of 5 or 6. However, the cost and skill required for the manufacture of the sail turbines are less and it is concluded that the present designs, which can be self starting if the trailing edge tension is appropriately set, may have application for 1 kW machines in developing countries.

8.3. P. D. FLEMING and S. D. PROBERT, *A proposed, three-sail Savonius-type wind rotor*, Cranfield Institute of Technology, S.M.E. Technical Memorandum, 1981.

The origin of the Savonius vertical-axis rotor, as derived from the Flettner rotor, is outlined. A three-sail self-starting Savonius type sail windwheel which is cheap to

produce and easy to repair is described. The sail profile varies, depending upon its position relative to the wind: a series of rollers on rods define the sail profile when rotating into the wind, but when both sail movement and wind directions coincide, the wind forms the sail into a useful, power harnessing shape. This, combined with the relatively lightweight rotor, results in higher rotational speeds and hence more power harnessed from the wind.

9. GENERAL

Two books deserve special mention with respect to small-scale wind energy utilisation.

9.1. D. MCGUIGAN, *Small-scale wind power*, Prism Press, Dorset, Great Britain, 1978.

This book deals with small-scale wind energy conversion systems and is aimed primarily, but not entirely, at the use of wind power in remote areas. Energy needs, site selection, wind measurement and wind energy estimation are evaluated. Various appropriate windmills are discussed, including Cretan sail, multi-blade, four arm, propeller and three vertical-axis designs. The merits of AC or DC electrical generation and the relative advantages of mains and low-voltage supply are described.

9.2. N. G. CALVERT, *Windpower principles—Their application on the small scale*, Griffin and Company Ltd., London, 1979.

This book provides a theoretical treatment of the small-scale application and technology of wind-powered machines, with particular emphasis on the sail wind-turbine. The background, fluid mechanics and component characteristics of wind-powered machines are reviewed, and the aerodynamics and possible geometries of the aerofoil are considered. Sails, sail-mills and vertical-axis mills are examined, and wind-turbine control and performance testing and wind measurement are discussed. The calculation of the power available from various types of windmills in various sites is treated, and the construction of a small pilot wind-power plant is discussed, with attention given to an evaluation of possible construction materials. Consideration is also given to windmills at sea and free-spinning, high-speed windmills, and to various means of energy storage.

ACKNOWLEDGEMENTS

The compilers of this state-of-the-art review and bibliography are especially grateful to the Energy Committee of the Science Research Council for financial support of

this project. The Information Retrieval Service of the Library at Cranfield Institute of Technology provided patient, constructive advice and painstaking help far beyond the call of duty, especially with respect to locating some of the more esoteric publications. 'In this work when it shall be found that much is omitted, let it not be forgotten that much likewise is performed...' Samuel Johnson, Preface to *Dictionary of the English Language* Vol. 1, p. 5, Straham Printers, London, 1755. Thus apologies are made in advance for important omissions, and these will be rectified in future versions if the missing references are brought to the attention of either compiler.

TECHNICAL, PERFORMANCE AND ECONOMIC DATA FOR SAIL-TYPE WIND-TURBINES

(This is taken from Reference 68)

(a) Technical Information

Type and reference	Rotor diameter (m)	Sail material	Spar material	Number of sails	Pump type and material	Pump size (cm)	Tower material and geometry	Axis height (m)	Water source	Major use	Total rated head (m)	Rated pumping output (m ³ /hr)	Major ^a fabrication skill required
Asia hybrid (3)	10.5	Cloth	Bamboo	8	Chain and discs, steel	12 bore	Wooden A-frame/pole	6.0		Theory	10.0	18.0	2
China (35)		Cloth	Wood	12			Wooden lattice, 4 legs						2
Cretan (8)	5.4	Cloth	Wood	6-8	Piston, brass	13 bore 15 stroke	Steel lattice, 4 legs	5.0	Open well	Irrigation	5.0	3.0	4
Madurai (3)	10.0	Cloth	Bamboo	8	Piston, P.V.C.	10 bore 13-35 stroke (variable)	8 wood poles	8.3	Open well	Test	9.2	1.6	4
Mardi (29,68)	6.1	Cloth		6	Peristaltic, rubber		4 wood poles	1.9	Canal	Test		1.9-5.7	4
NAIE (76)	5.5	Dacron	Steel tube	6	Piston, P.V.C.		8 wood poles	8.2	Lake	Aquaculture	4.3	1.1	3
Omo-11 (5)	3.4	Dacron	Steel pipe	6	Piston, steel	7.6 bore 17.8 stroke	Steel lattice, 3 legs	4.0	River	Irrigation	2.8	1.8	4
Omo-14 (5)	4.3	Dacron	Steel pipe	8	Piston, steel	7.6 bore 17.8 stroke	Steel lattice, 3 legs	4.0	River	Irrigation	2.8	3.8	4
Omo-16 (5)	4.9	Dacron	Steel pipe	8	Piston, P.V.C.	7.6 bore 17.8 stroke	Steel lattice, 3 legs	4.0	River	Irrigation	2.8	7.3	4
Sarvodaya (68)	4.9	Cloth	Bamboo	8	Piston, P.V.C.	20.3 bore 15.2 stroke	8 wood poles	7.4	Open well	Irrigation	2.0	7.4	4
Thai bamboo (3)	7.0	Bamboo mat	Bamboo	6	Pallet, wood	21×23 trough	2 wood poles	3.6	Salt water canal	Salt production	0.6	15.0	1
Thai cloth (3)	7.0	Cloth	Wood	6	Pallet, wood	21×23 trough	2 wood poles	3.6	Salt water canal	Salt production	0.6	48.5	1
UNICEF (68)		Cloth			Piston		4 wood poles		Storage tank	Test			
Windworks (68)	7.6	Dacron	Wood	6			Steel octet truss	15.0		Test			4

^a Skill levels: (1) Rough carpentry. (2) Good carpentry. (3) Metal drilling and cutting. (4) Metal welding. (5) Machine lathe operation. (6) Fine carpentry. (7) Fibreglass reinforced plastic moulding. (8) Steel casting. (9) Gear making. (10) Hydraulic fitting.

Type	Type of power transfer	Estimated construction time (man-hours)	Swept area of rotor (m ²)	Starting wind velocity (m/sec)	Control type and cut-out velocity (m/sec)	Rated wind velocity (m/sec)	Rated speed (rev/min)	Tip speed ratio (u/v)	Rated output corrected to 10m head (m ³ /hr)	Corrected rated output per unit swept area (m ³ /hr/m ²)	Overall aerodynamic and mechanical efficiency (per cent)
Asia hybrid	Open link chain	200	86.6	1.6	Manual furling above 6	5.6	12	1.2	18.0	0.21	4.8
China	Wood gears	80									
Cretan	Crankshaft	160	22.9	2.2	Manual furling above 4	3.5	25	2.0	1.5	0.07	6.1
Madurai	Crankshaft	500	78.5	1.7	Manual furling above 4.5	2.2	12	2.8	1.8	0.02	8.6
Mardi	Bevel gear		29.0		Manual furling						
NAIE	Crankshaft	300	23.7		Manual furling	3.5	25	2.0	2.6	0.11	6.8
Omo-11	Crankshaft		8.8		Manual furling above 5	4.6			0.5	0.06	2.3
Omo-14	Crankshaft		14.3		Manual furling above 5	4.6			1.1	0.07	3.2
Omo-16	Crankshaft		18.7	2.5	Manual furling above 5	4.6			2.0	0.11	4.5
Sarvodaya	Crankshaft	400	18.7		Manual furling above 6	5.4	30	1.1	1.5	0.08	2.1
Thai bamboo	Open link chain	120	38.5		Manual furling above 6	4.2	25	2.4	3.1	1.08	4.4
Thai cloth	Open link chain	120	38.5	2.8	Manual furling above 6	3.7			8.3	0.22	17.4
UNICEF	Crankshaft				Manual furling						
Windworks	Bevel gear	400	45.4		Manual furling						

Table 1. Greek Sail Rotor Types — (c) Economic Information

Type	Annual ^a water output (m ³)	Assumed normal lifetime (years)	Initial installed cost (\$US)	Total lifetime spare parts cost (\$US)	7% interest annual charge (\$US)	Depreciation ^b annual charge (\$US)	Spare parts annual charge (\$US)	Total annual charge (\$US)	Unit water cost (\$US per m ³)
Asia hybrid	21,600	10	350	270	24.5	35.0	27.0	86.5	.004
China									
Cretan	1,800	20	480	170	33.6	24.0	8.5	66.1	.037
Madurai	2,160	10	400	266	28.0	40.0	26.6	94.6	.043
Mardi									
NAIE	3,168	10	500	200	35.0	50.0	20.0	105.0	.033
Omo-11	600	20	350	75	24.5	17.5	3.8	45.8	.076
Omo-14	1,320	20	360	115	25.2	18.0	5.8	49.0	.037
Omo-16	2,400	20	400	150	28.0	20.0	7.5	55.5	.023
Sarvodaya	1,800	10	300	200	21.0	30.0	20.0	71.0	.039
Thai bamboo	3,720	10	165	162	11.6	16.5	16.2	44.3	.012
Thai cloth	9,960	10	246	214	17.2	24.6	21.4	63.2	.006
UNICEF									
Windworks			600						

^a 1,200 hours of operation at rated output assumed per year.

^b Straight line depreciation over assumed normal lifetime.

APPENDIX C

PROPOSED 1.25 m DIAMETER WIND TUNNEL

WIND TUNNEL DESIGN

The existing wind tunnel, (see Plate 2), described in Chapter 11, section 11.1, suffered from many limitations (i.e. the fan blades had been cut away and the ratio between rotor and duct diameter was relatively small) resulting in non uniform velocity profiles. To overcome this, a more appropriate wind tunnel design was considered.

There were three options;

1. Modification of an existing "square-section" wind tunnel, see Plate 6;
2. Construction of a new duct, using another second-hand fan; or
3. Construction of an entirely new wind tunnel (i.e. a new fan and a new duct).

1 MODIFICATION OF AN EXISTING SQUARE-SECTION WIND TUNNEL

This existing tunnel (see Plate 6) was driven by a centrifugal fan. This type of fan was considered unsuitable to create a uniform velocity profile. Also the duct-work was too small to adequately accommodate the testing of the vertical-axis wind-turbine. Accordingly this option was dismissed.

2 NEW DUCT WITH SECOND-HAND FAN

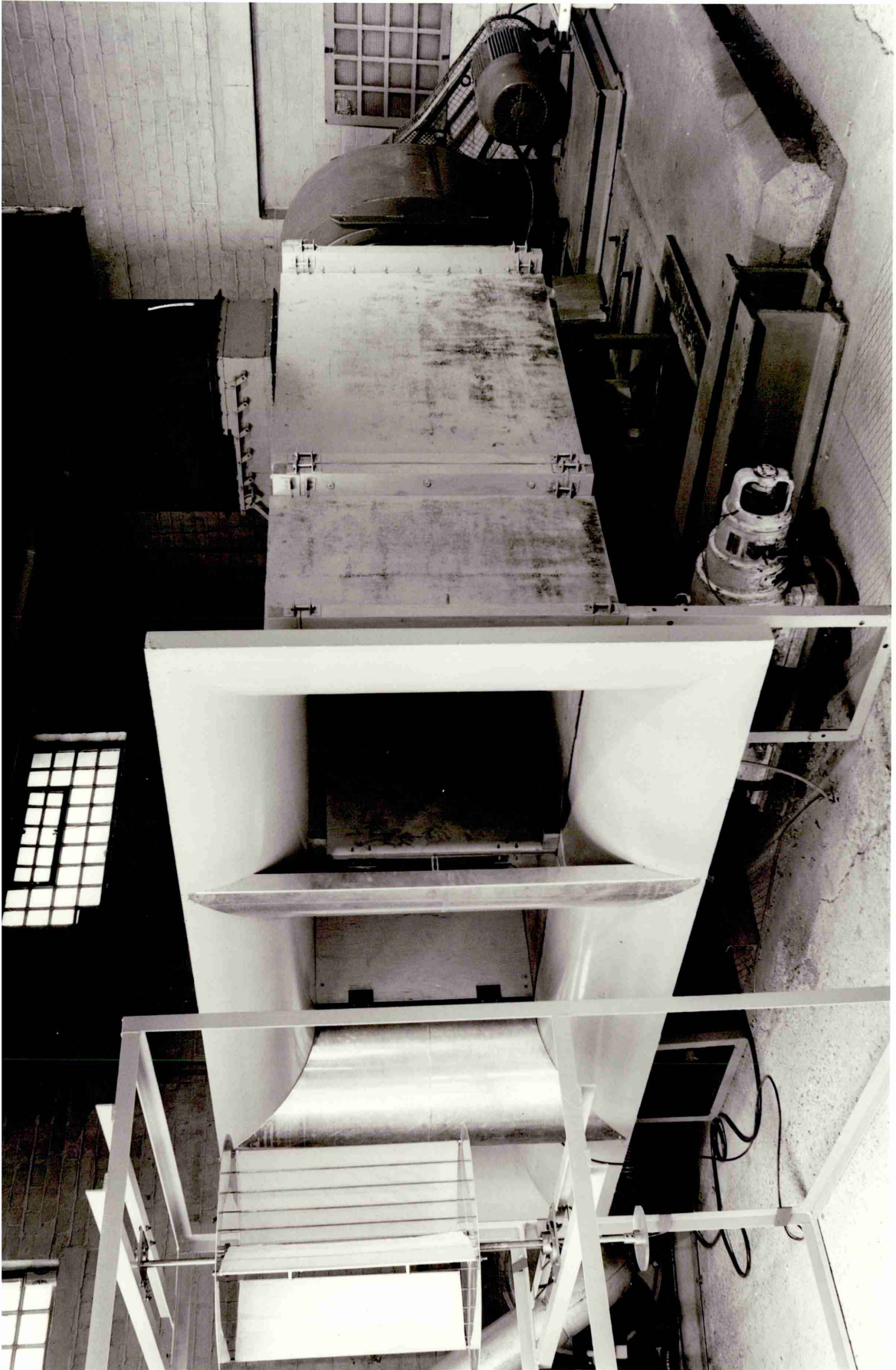
This option is acceptable provided that the second-hand fan is guaranteed to produce a uniform air flow. From previous experience with the existing wind tunnel this was not considered likely. This option was also dismissed.

3 ENTIRELY NEW WIND TUNNEL

A completely new, larger wind tunnel was considered the most appropriate option. The new axial-flow fan would provide uniform wind speeds and the larger diameter duct reduce the blockage effects.

Plate 6

Square-section wind tunnel.



APPENDICES
Appendix C

To generate a variety of different wind speeds in the duct, a variable speed fan was required. This somewhat limited the choice of axial-flow fans available. Following a survey, the most appropriate fan was considered to be a 1.22 m diameter variable speed axial flow model, manufactured by Myson of Colchester.

The duct-work (1.27 m diameter) would then be fabricated from standard sheet metal sizes in 2 m sections, with a total length of 8 m (see Fig. 86).

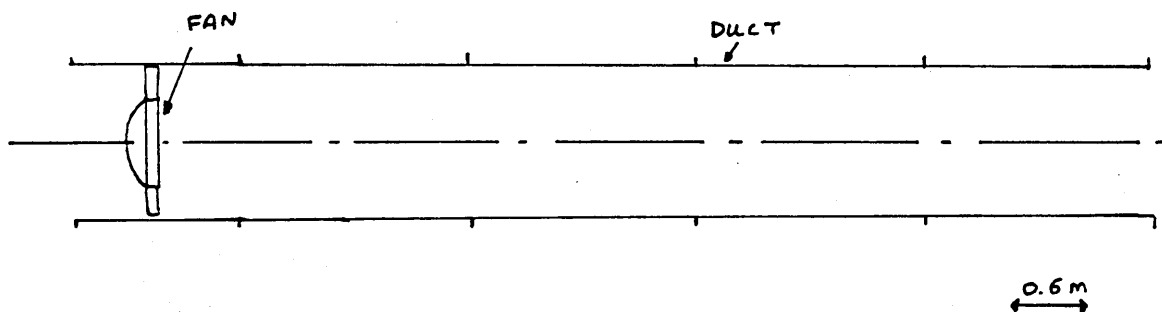


Fig. 86. Proposed wind tunnel.

A fan after-body and flow straighteners would be required to obtain uniform velocity profiles.

The approximate total cost of such a system (at 1981 prices) was £4,500.

This cost was considered prohibitive and all the tests reported in this investigation (see Chapter 12) were undertaken with the existing wind tunnel as described in Chapter 11.

APPENDIX D

DEMONSTRATION PROJECT: TWO TYPES OF POWER AUGMENTED, WIND-PUMPS

TECHNICAL DESCRIPTION

The proposed project aims to demonstrate two different types of cheap, self-regulating wind-turbines for driving peristaltic pumps. Research concerning the two small sail-type wind-turbines has shown power increases of more than 50 per cent by utilising cheap, simple power augmentation devices on the horizontal-axis sail-type wind-turbine.

The project would demonstrate the use of wind-driven water pumps for:-

1. raising water in less-developed countries for crop irrigation, animal and human use, and
2. crop irrigation and stock watering in developed countries.

Each power augmented wind-turbine would harness approximately 200 W of the wind's energy in a wind speed of 5 ms^{-1} at the level of the rotor. The mass flow rate of water pumped would be of the order of 10 to 15 kgs^{-1} , through a height of 1 m at atmospheric pressure. It is anticipated that the wind-turbine would operate for approximately 12 hours per day for 340 days per year (with self-regulating mechanisms).

SAIL-TYPE WIND-TURBINES

These flexible sail-type, low cost rotors are capable of harnessing energy from relatively low speed winds ($\sim 5 \text{ ms}^{-1}$). They are self-starting and produce relatively high torques at low rotational speeds making them suitable for water pumping.

Horizontal-axis wind-turbine

The 2.5 m diameter horizontal-axis wind-turbine will have 6 triangular sails and be coupled, via appropriate gearing, to a peristaltic pump. The wind-turbine construction (see Fig. 87), has wire stays connecting the tips of the 6 radial spars. Tip-fins will be fastened to these stays to augment the wind-turbine power output.

APPENDICES
Appendix D

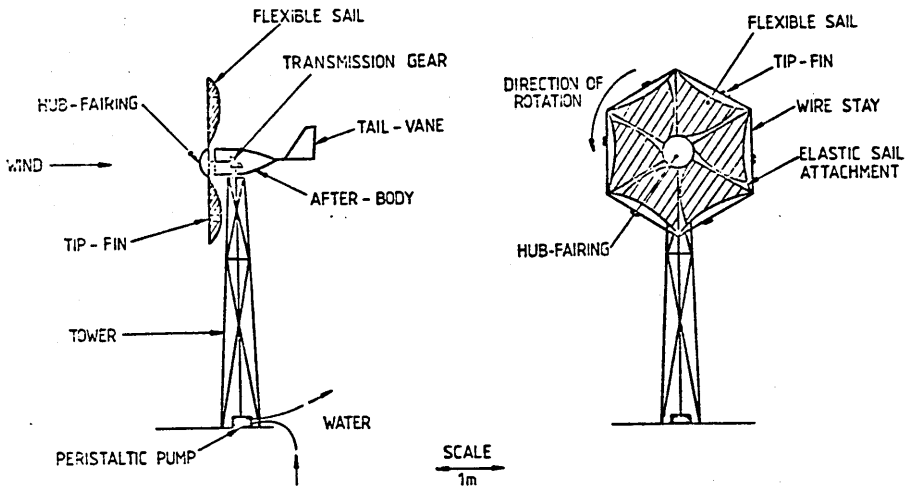


Fig. 87 Horizontal-axis demonstration wind-turbine

The rotor will be positioned on top of a 4 m high lattice-structure tower. To enable the rotor to be turned to face the wind, a tail-vane will also be attached. The wind-turbine would then be maintained facing the wind. The rotational energy of the wind-turbine would then be transferred to the vertical shaft by the bevel gear (see Fig. 87). The vertical shaft directly drives the peristaltic pump so pumping water and minimising transmission inefficiencies.

Tip-fins

These cheap, basic, small auxiliary surfaces, capable of augmenting the wind-turbine power outputs, are easily fastened to the peripheral stays of the rotor.

Centre-body

A hub-fairing (which when used in conjunction with an after-body, is referred to as a centre-body) gives substantial augmentation for sail-type turbines. These "flow deflectors" will be attached to the rotor's axial shaft to minimise the "hub losses".

Vertical-axis wind-turbine

The vertical-axis wind-turbine (of a cylindrical appearance 2.5 m high by 2 m diameter) with flexible sails would be mounted upon a 3.5 m high tower. The central shaft of the rotor would extend down to ground level to drive the peristaltic pump (see Fig. 88).

APPENDICES
Appendix D

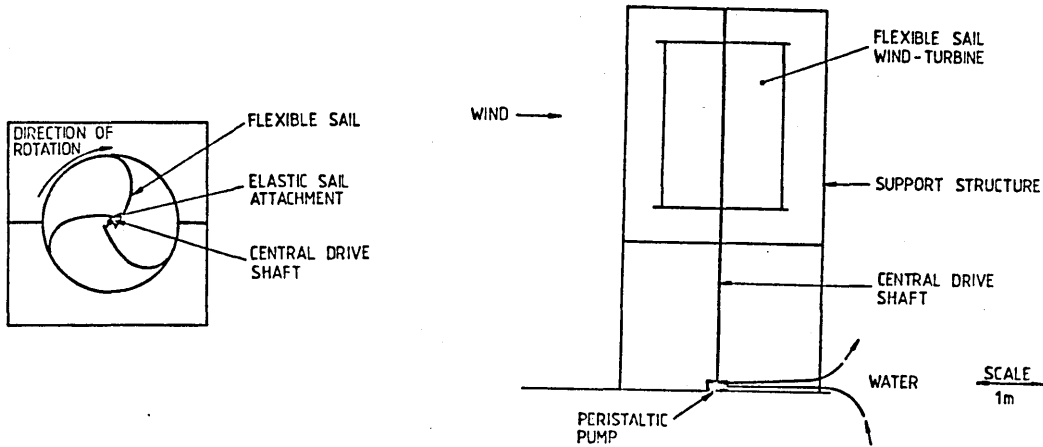


Fig. 88. Vertical-axis demonstration wind-turbine.

This rotor does not need to be "turned to face the wind" as it is intrinsically non-directional and self-starting. The rotor's rotating shaft directly drives the peristaltic pump so virtually eliminating transmission losses.

WIND-TURBINE SELF-REGULATION

Elastic attachments or shock chord would be used to hold the trailing edges of the sails to the wind-turbine spars. These attachments would yield or break respectively in relatively high speed winds, allowing the sails to "flap" so providing a considerable degree of self-regulation. However the sails would need manual furling during, infrequent, excessively high speed winds.

PERISTALTIC PUMP

The peristaltic pump — employing a simple conveyance concept. involving few moving parts — is a robust pump that can be readily serviced by semi-skilled personnel: it need not be constructed from expensive materials. Because it has no mechanical drive into its pumping chamber, sealing problems do not occur and simplicity is maintained.

APPENDICES
Appendix D

DEMONSTRATION SITE

The demonstration would be sited at the edge of the operational airfield on the Cranfield campus. Anemometry towers and measuring systems would be constructed on the site and data acquisition equipment would record wind speed, barometric pressure, rotor rotational speed, torque and the mass flow rate of pumped water every half hour. The data so collated would be continuously compared with that obtained at the air traffic control tower some 300 m away.

CONCLUSION

Power augmented sail-type wind-turbines driving water pumps do not exist yet commercially, although there are a variety of commercial propeller and multi-vane horizontal-axis wind-turbines available. The vast majority of the turbines are designed for electricity generation, not direct water pumping, and are relatively expensive.

These self-regulating "wind-pumps" would be designed for simplicity of manufacture, whilst maximising the pumping power harnessed from the wind. They can be used for many water pumping applications throughout the developed, as well as the developing, world.

APPENDIX E
EQUIPMENT USED

WIND TUNNEL

AC Commutator motor (Serial Number R212480)	Manufactured by — THOMSON-HOUSTON AND COMPANY LIMITED, Rugby
Speed 1250/400/20 r.p.m.	Reconditioned by — R.R. BRITON, Shepton Mallet, Somerset
Power 9/2/0.1 horse power	

MONITORING EQUIPMENT

Micro-manometer	Manufactured by — FURNESS CONTROLS LIMITED, Sussex
Calibration Temperature	23 C
Input Volage	240 V
Output Volage	0 to 1.0 V
Slow Time Constant	2 s
Dial Marking Pressure	0 to 30 per cent and 0 to 100 per cent

The instrument had an accuracy of 1 per cent in any of the five, full scale deflection, ranges. (1, 3 ,10, 30 and 100 per cent).

Electronic counter	15 Mhz	TC12A
--------------------	--------	-------

Pitot-static tube

Various spring balances

APPENDIX F
EXPERIMENTAL ERRORS

Experimental errors arose from the following sources:-

1. Wind speed
2. Wind-turbine blockage
3. Dynamometer
4. Sail area
5. Sail angle
6. Rotor speed

As outlined in Chapter 11 section 11.1, uniform velocity profiles were difficult to attain. Thus no attempt was made to present the data (see Chapter 12) in the conventional "power coefficient versus tip-to-wind speed ratio", format. Whilst the combined effect of a non-uniform velocity profile and relatively large blockage would have created unreasonable errors, these errors are less applicable when the data are presented (as in Chapter 12) on a comparative basis. The same (or almost same) wind régime acts upon all the tested wind-turbines and so these measurement errors were not compounded and are thus relatively unimportant with respect to the data presented (see Chapter 12). This implies that all the data recorded in this investigation cannot be accurately compared with data obtained from other similar wind-turbines, that have not been tested in the test facility detailed in Chapter 11.

Dynamometer errors arose from the slight oscillations set up by the rotating wind-turbines. These were most apparent in the guide pulleys and in the spring balance needle. These errors are estimated to be of the order of 4 per cent of the measured torque.

Sail angle and sail area errors are due mainly to the accuracy to which their respective dimensions were measured. These and the error of the photo-cell and timer (used to measure the rotor speed) are considered negligible.