9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE
AUCKLAND, 8-12 DECEMBER 1986

Propeller Wind Turbine Rotor Design and Testing

D. H. COX[1], R. J. SANDERSON[2], L. T. KHOO[3] and R. D. ARCHER[3]

[1]Qantas Airways Ltd, Mascot, Sydney.
[2]Numeric Solutions, Sydney.
[3]School of Mechanical & Industrial Engineering, University of NSW, Australia.

ABSTRACT

In response to a need to provide water at the Mawson Antarctic base, one proposal has been to melt snow using wind power in prevailing average wind speeds of 14 ms^{-1}

Two and three bladed rotors have been designed using minimum loss theory to produce a nominal 1 kW at design speed. Computer aided manufacture of blades has been accomplished in various materials for blades up to 1.2 m diameter. Blade section profile has been limited so far to NACA 2412 and Clark Y for which adequate data over a wide range of Reynolds numbers is available, and also for which there is no re-entrant concave shape. Confirmation of aerodynamic performance in wind tunnel tests has required the development of a direct torque measurement technique. Results of tests at half of nominal Reynolds number ($\simeq$ 200,000) yield a peak performance with 85% of that predicted.

NOMENCLATURE

A = rotor disc area, $\frac{\pi}{4}D^2$

B = number of blades in rotor.

c = local airfoil chord.

C_ℓ = local, airfoil lift coefficient.

C_p = $P/\frac{1}{2}\rho AV^3$, power coefficient (efficiency).

D = rotor diameter, 2R.

HAWT = horizontal axis wind turbine.

ℓ/d = local, airfoil lift/drag ratio.

N = rotor shaft speed, r.p.m.

P = rotor shaft power.

r, R = rotor local, tip radius.

RN = Reynolds number based on local chord, c.

T = rotor thrust.

TSR = tip speed ratio = $\frac{1}{\lambda}$

V = free stream velocity, or wind speed.

ρ = air density.

λ = $V/\omega R$, free stream/rotor tip speed = $1/TSR$.

ω = rotational speed, $\frac{2\pi N}{60}$

INTRODUCTION

Meteorological conditions at the Mawson Antarctic base are characterised by strong morning katabatic winds blowing from the SE away from the high polar plateau, a high average speed of above 14 ms^{-1}, a small period of calm (5%) per year, and hurricane strength storms with gusts exceeding 50 ms^{-1}, (Bowden etal, 1980). This unusual wind structure, Figures 1 and 2, combined with a significant energy potential in gusts, (Bowden etal, 1981) led to the proposal for the use of fixed arrays of small (fast response) 1 kW wind turbines, which could exploit the highly directional and high level of wind energy. A pressing problem for Mawson is water supply and a natural solution to this is therefore to use wind energy as a heat source to melt snow.

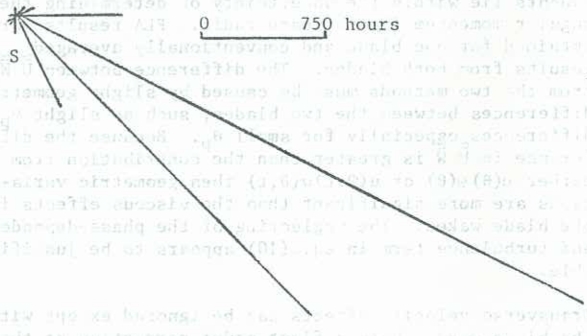


FIGURE 1
WIND ROSETTE - MAWSON
(Bowden etal, 1980)

The design of a rotor for such a wind turbine is thereby freed from the constraints of providing frequency and voltage coupling to a grid and can choose an optimum power condition appropriate to maximum energy production. The unusual nature of the Mawson wind frequency distribution (Bowden and Adler, 1980) Figure 2, also favours a rotor design with rated speed to mean wind speed ratio approaching unity instead of the ratio of ~ 2 for the more usual Weibull distribution. The analysis of optimum conditions for propellor type rotors (HAWT) suggests that peak performance (power coefficient $C_p \sim 0.3$) will occur at low advance ratios $\lambda \sim 0.14$ (Sanderson and Archer, 1983). In the high average winds of Mawson this implies a tip speed ratio (TSR= $\frac{1}{\lambda}$ =7.4) and a high tip speed $\sim$100 ms^{-1}

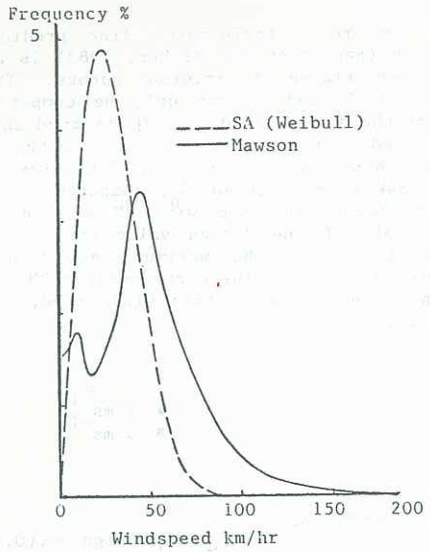


FIGURE 2

WIND FREQUENCY DISTRIBUTION - MAWSON AND PT. LINCOLN, S.A. (Bowden & Adler, 1980)

For a 1.2 m diameter rotor designed to generate 1 kW, in mean winds of 14 ms^{-1}, r.p.m. would be ~1600 and centrifugal g-loading ~17000. In 50 ms^{-1} gusts, extreme operating conditions would apply: 6000 r.p.m., supersonic tip speed and 200,000 g loading. Since it is desirable not to have to provide for furling or braking, it is necessary to adopt a higher design advance ratio λ (lower TSR) and accept, therefore, a performance lower by 5-10% than the peak optimum value of C_p=0.3.

ROTOR DESIGN AND MANUFACTURE

Following experience with design, manufacture and test of two small 2 bladed rotors (1 & 2 of Table), each intended to generate ~1 kW at 14 ms^{-1}, two, slower-moving, larger, 1.2 m diameter rotors were designed to operate at a tip speed ratio, TSR=3 (λ=0.33) and also to generate 1 kW at 14 ms^{-1}.

The early designs revealed problems with low RN or scale effect, high g-loading, strength, stiffness, and vibration. While the blade chord predicted by the theory leads to approximately constant RN radially, the relevant value of RN was appropriate to laminar separation and consequent loss of performance (due to low ℓ/d) together with rapid changes in performance with airspeed (due to changing effect of RN on ℓ/d).

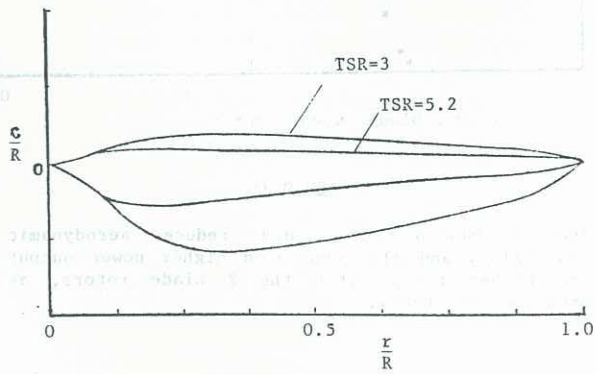


FIGURE 3

BLADE CHORD DISTRIBUTION - EFFECTS OF TSR

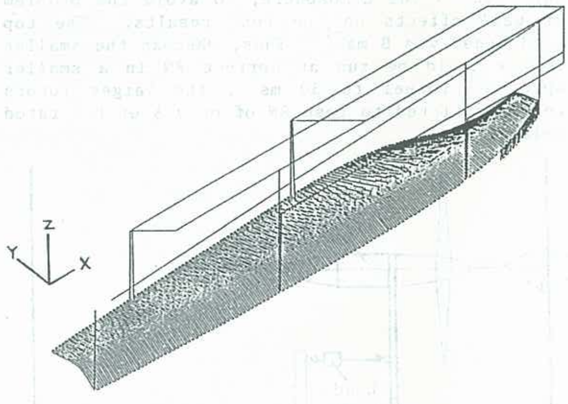
The influence of TSR on blade chord is shown in Figure 3. It is apparent that RN is maintained constant for the same rotor diameter, thus the increase in RN for the larger diameter (1.2 m) rotors improves the blade ℓ/d by upwards of 100%, and the optimum C_p, while still lower than the peak, due to operating at an off peak TSR (3 instead of 5.7), is only marginally less than that of the smaller rotors designed for the higher TSR. The 3 bladed rotor was needed to check for (1) the predicted increase in performance of 3 over 2 blades (even though there would be an off-setting loss in performance due to smaller blade chord and hence lower RN), and for (2) potential improvement in aerodynamic (nodding and yawing) stability, and vibration.

Strength checks at an over-load condition appropriate to a wind speed of 50 ms^{-1} established the integrity of the wooden blades. The centrifugal loading, although large, is less than that due to bending at the root (Cox 1984).

Manufacture of all blades was by a Makino 3-axis mill under computer control from a PDP11-60 (Figure 4). Only one side at a time was machined from a solid block, the work being turned over and set in plaster-of-paris for the reverse side machining. Hand finishing only was needed to smooth the surface machine cuts and minor chipping of the 2 wooden rotors. These were then coated with clear lacquer giving a smooth finish. The 2 bladed wooden rotor was machined integral with the hub from a single block, whereas each blade of the 3 bladed rotor had to be individually machined, fitted to a wooden hub, and statically balanced.

FIGURE 4

CAM TOOL PATH - ROTOR BLADE



TEST PROCEDURE

Testing of the 2 smaller rotors brought to light the need for a direct means of measuring torque and speed of the rotor shaft. These tests had used a rewound Bosch LJ automobile alternator (Bowden etal, 1981) for applying load. After calibration (Belcastro and Starrett, 1984), the alternator could be used to measure shaft power. This procedure lead to satisfactory results (<8% scatter) for power measurement in the small open jet wind tunnel (0.76m D) (Figure 7c), but in a larger wind tunnel operating at lower speeds scatter increased to an unacceptable 25% (Vidakovic 1983). Consequently, a simple flexible cantilever beam and strain gauges were installed at the rear of the alternator housing (Figure 5) to read out torque directly, and calibration was linear.

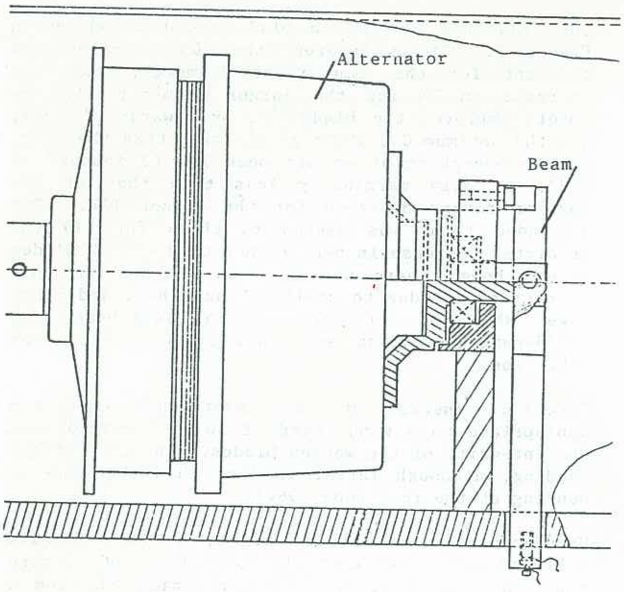


FIGURE 5

CANTILEVER BEAM TORQUE RESTRAINT

A photo diode detector, reading the transmitted light through a disc with peripheral holes, was installed on the rotor shaft to acquire r.p.m. directly. Thrust was also measured directly by a load cell incorporated in the test rig (Figure 6). The larger diameter rotors required the use of the largest available test section of 10ft x 10 ft (3.05 x 3.05 m). The test section was run open to the atmosphere, to avoid the problem of wall effects on the test results. The top wind speed was 8 ms^{-1}. Thus, whereas the smaller rotors could be run at correct RN in a smaller open jet tunnel to 30 ms^{-1}, the larger rotors were restricted to test RN of only ½ of the rated values.

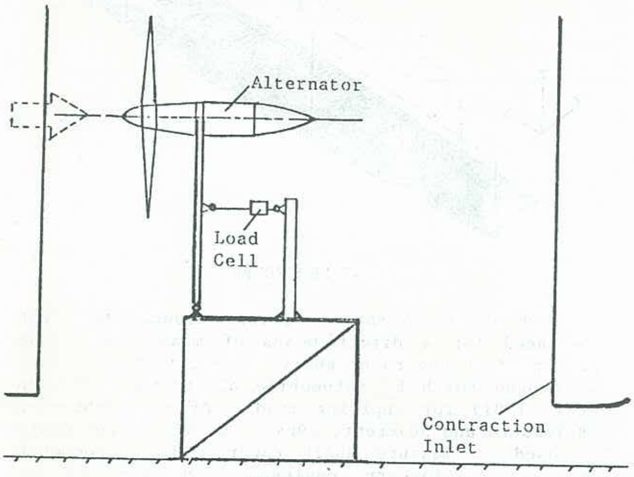


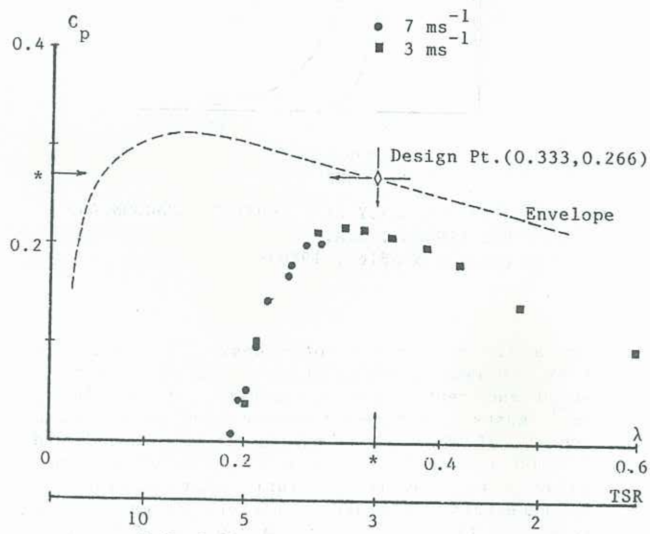
FIGURE 6

WIND TUNNEL TEST ARRANGEMENT

RESULTS & DISCUSSION

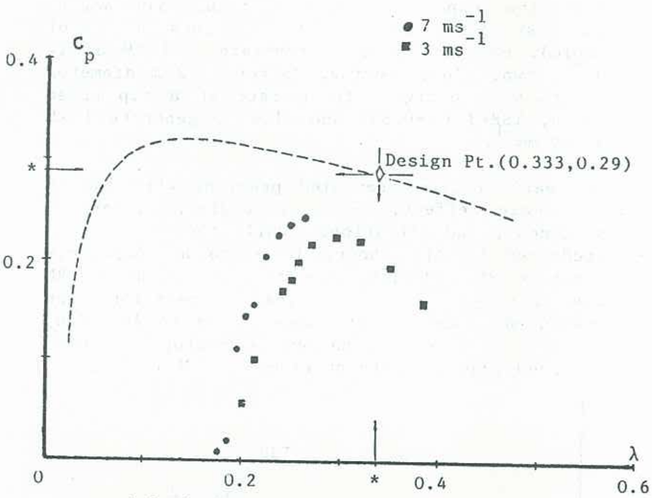
The use of direct power measurement increased the accuracy of test results (scatter reduced to <5%).

The optimum rotor performance line predicted by the theory (Sanderson and Archer, 1983) is a locus of peak performance of different rotors. Thus the results for C_p and C_T can only be compared with theory at the design point λ*. Quite good agreement is obtained for thrust, C_T, ie: within 95%. However, there is a shortfall, depending on RN, of the peak test value of C_p, compared to theory. The test values increase with RN as expected up to about 85% of the design value for both 2 and 3 blade rotors at the maximum test wind speed available of 8 ms^{-1}. The corresponding RN is about ½ of the rated value at this wind speed, (Figures 7a and 7b).



1.2m 2 blade, wooden rotor.

Figure 7a

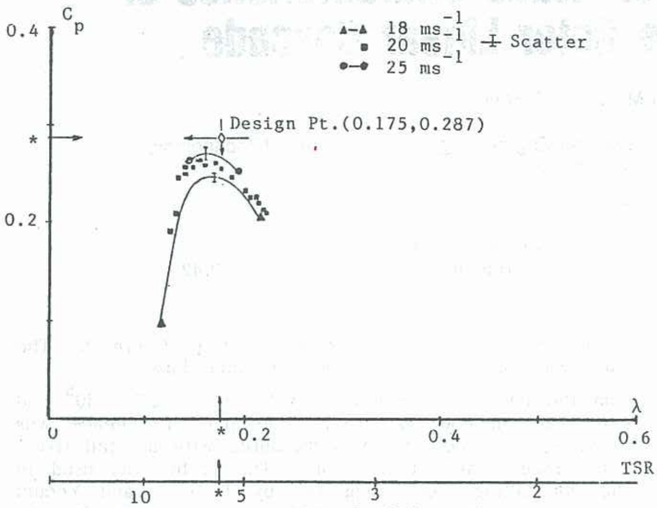


1.2m 3 blade, wooden rotor.

Figure 7b

The 3 bladed rotor did reduce aerodynamic instability and also generated higher power output and higher thrust than the 2 blade rotors, as predicted by theory.

Tests at the correct RN on smaller 0.6m D aluminium 2 blade rotor had yielded peak power within 87% of design, and also showed a trend of increasing power with increasing RN, (Figure 7c).



0.6m 2 blade, aluminium rotor

Figure 7c

FIGURE 7

ROTOR POWER TEST RESULTS, C_p versus λ

The polycarbonate rotor lacked stiffness and its flexibility lead to unacceptable deformation under load.

CONCLUSION

Optimum loss theory for design of propellor wind turbines can be expected to give a correct prediction of shaft power generation, only if RN effects are fully allowed for and will therefore give an optimistic 10-15% over estimate in small rotors (1 kW) operating in subcritical RN's where airfoil characteristics undergo large non linear changes. The accuracy of prediction can be expected to improve for larger rotors operating above the critical RN range.

Off-design operation produces substantial fall in power output indicating that loading should attempt to operate the rotor at constant TSR irregardless of wind speed.

Of the two sizes tested, the larger, slower, turning rotors are preferable in the conditions of Mawson base.

REFERENCES

Bowden, G.J; Barber, P.R; Jenkin, M.F; Starrett, R.P; (1981): "Small Wind Gust Generator Arrays for the Antarctic", Wind Engineering, Vol.5 No.4, 227-234.

Bowden, G.J; Adler, Joan; Dabbs, T; Walter, J; (1980): "The Potential of Wind Energy in Antarctica", Wind Engineering, Vol.4 No.3, 163-176.

Bowden, G.J. & Adler, Joan(1980): "Wind Generator Choice for a Remote Location", Wind Engineers, Vol.4 No.3, 155-162.

Barker, P.R., Bowden, G.J. and Clegg, R.J.,(1984): "The Winds of New South Wales", Energy Authority of New South Wales., EP-3 180 pages.

Cox, D.H. (1983): "Horizontal AxisWind Turbine Test", BE Thesis, University of New South Wales.

Cox, D.H. (1984): "A Preliminary Design Study of 2 Wind Turbine Generators for use in Antarctica", University of New South Wales, School of Physics, internal report.

Khoo, L.T. (1985): "Horizontal Axis Wind Turbine Wind Tunnel Testing", BE Thesis, University of New South Wales.

Sanderson, R.J. and Archer, R.D. (1983): "Optimum Propeller Wind Turbines", Journal of Energy, AIAA, Vol.7 No.6, 695-701.

Belcastro, P. & Starrett, R.P, (1984): "HAWT Alternator Calibration", Univeristy of New South Wales, School of Mechanical & Industrial Engineering, internal report.

Vidakovic, S.S. (1984): "Horizontal Axis Wind Turbine Wind Tunnel Testing", BE Thesis, University of New South Wales.

Table: Rotor Design Features.

Rotor	Material	B	D	TSR*	λ*, C_p*	N*, g*	Airfoil	C_p*, $\frac{\ell}{d}$*	RN* @ 0.7R	Reference
-	-	-	1	-	-	rpm, -	-	- , -	-	-
1	Aluminium	2	0.6	5.7	0.175,0.28	2550,21000	NACA2412	0.8,30	60000	Cox, 1983 Vidakovic, 1984
2	Polycarbonate plastic polymer lexan	2	0.75	5.2	0.192,0.29	1780,14000	ClarkY,11.7%	1.0,43	100000	Cox,1984
3	High grade Spruce	2	1.2	3.0	0.33,0.28	670,3000	ClarkY,11.7%	0.85,60	200000	Cox,1984
4	Lam.Q'ld.Maple	3	11	3.0	0.33,0.27	670,3000	ClarkY,11.7%	1.0,50	133000	Khoo,1985

* Design point, V=14 ms^{-1}