

# The Performance of Delta-Wing Bladed Wind-Turbines

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**SUMMARY** A description is given of a new type of horizontal axis, fixed pitch, wind-turbine employing delta-wing blades. Performance data are presented and it is shown that a power coefficient of approximately 0.4 can be achieved and that maximum torque is generated at zero rotor speed.

## NOTATION

|                      |  |
|----------------------|--|
| $C_L$                | Lift coefficient based on planform area  |
| $C_P$                | Power coeff. = work rate / $\{ \frac{1}{2} \rho U_\infty^3 (\pi D^2 / 4) \}$     |
| $C_T$                | Torque coeff. = torque / $\{ \frac{1}{2} \rho U_\infty^2 (\pi D^2 / 4) (D/4) \}$ |
| $D$                  | Overall diameter of rotor  |
| $j$                  | Surface area of flaps/delta surface area   |
| $m$                  | Delta surface area / $(\pi D^2 / 4)$   |
| $U_\omega$           | Blade speed at periphery of rotor  |
| $U_\infty$           | Wind speed   |
| $U'_\infty$          | Axial component of velocity at rotor   |
| $\alpha$             | Blade incidence angle  |
| $\eta_{\text{BETZ}}$ | Betz efficiency = $(27/16) C_P$  |
| $\Pi$                | Power specific tip speed (see section 6)   |
| $\rho$               | Air density  |

## 1 INTRODUCTION

One way of simplifying wind-turbine-rotor fabrication is to use flat-plate blade surfaces. It appears that the most effective form of flat plate airfoil, over a wide range of incidence angle, is the sharp-edged delta wing. A disadvantage of delta wings relative to conventional wings is, for a prescribed lift coefficient, a relatively high drag coefficient. A horizontal axis wind-turbine incorporating delta-wing blades equipped with flap-like extensions is illustrated diagrammatically in Fig. 1.

Recently fairly extensive wind-tunnel testing was carried out on model delta-wing bladed turbines

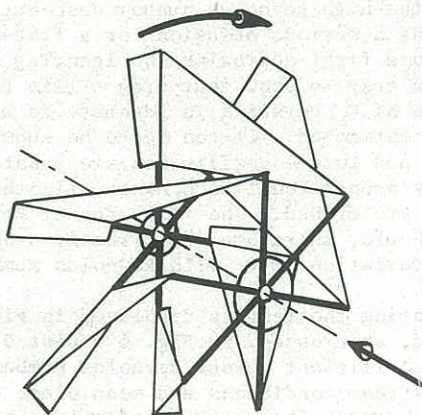


Figure 1 Basic arrangement of a delta-wing bladed wind-turbine rotor

(Kentfield and Norrie, 1977). This work was aimed at establishing, at least to a first approximation, an optimum configuration capable of producing maximum torque at zero speed and hence particularly suitable for the direct drive of simple water pumps etc. It was during the course of this work that the benefits of flap-like blade extension surfaces, as depicted in Fig. 1, were demonstrated. The purposes of the present paper are to report more recently obtained results and to give an indication of the development potential of the delta-wing-bladed turbine (delta-turbine) concept.

## 2 ROTOR GEOMETRY

The geometry of an individual blade of an eight-bladed configuration optimized during the course of model tests (Kentfield and Norrie, 1977) is shown, in a normalized form all dimensions being expressed as multiples of the rotor diameter  $D$ , in Fig. 2 and

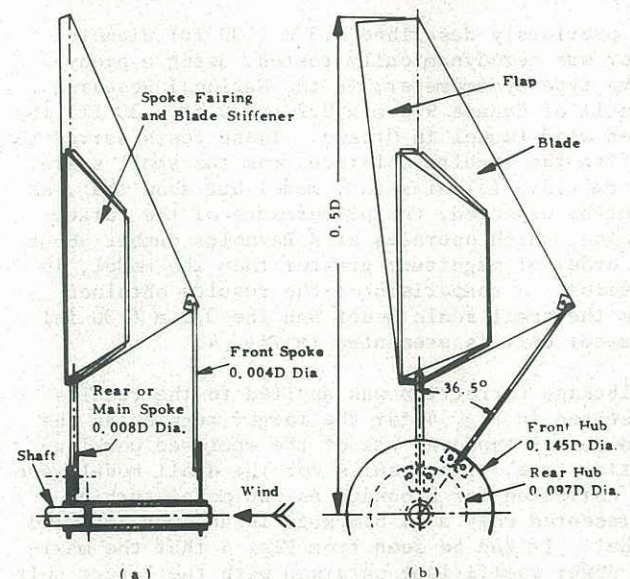


Figure 2 A single blade of an eight bladed rotor  
(a) Side view with hub sectioned  
(b) Head-on view looking downwind

3. Figures 2 and 3 are based on the actual engineering design of a prototype rotor of 3.3 m (130 in) diameter.

Each blade and integral flap surface of the 3.3 m (130 in) diameter rotor was made from 1.5 mm (16G) sheet steel. This component was plug-welded to the main, or rear, spoke which was located on the



pressure surface of the blade. A combined spoke fairing and blade stiffener made from 0.75 mm (32G) sheet steel, was spot welded to the flap and blade surface and was also plug welded to the main spoke.

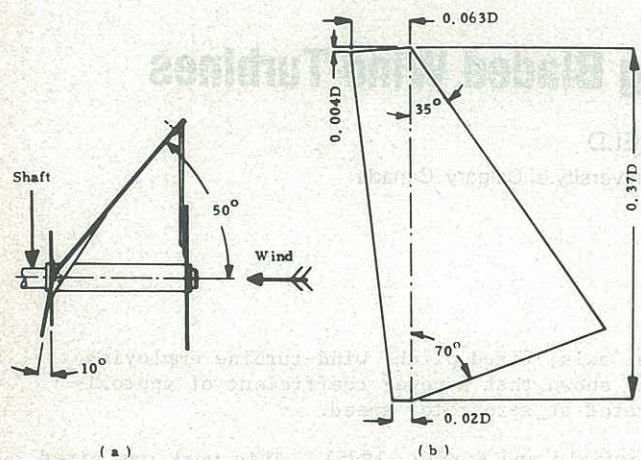


Figure 3 Details of rotor shown in Figure 2  
(a) View, towards hub, looking radially on to a main spoke  
(b) Flat generation of a blade and flap surface.

The rear spoke was made of thick-walled tubing, the front spoke was made from mild steel rod. For ease of transportation each spoke was bolted, rather than welded, to the welded steel hub.

Other methods of construction are, of course, possible. For example for small rotors plywood can be used for the blade and flap surfaces. For large machines the blades can be based on frameworks, made from structural steel, suitably covered (Kentfield, 1978).

### 3 PERFORMANCE

The previously described 3.3 m (130 in) diameter rotor was aerodynamically tested, using a prony-brake type dynamometer, in the National Research Council of Canada 9.2 m x 9.2 m (30 ft x 30 ft) low speed wind tunnel in Ottawa. These tests served to confirm the results obtained from the small scale, 394 mm (15.5 in) diameter, model but show that, as might be expected, the performance of the larger turbine, which operates at a Reynolds number about one order of magnitude greater than the model, is superior. A comparison of the results obtained from the small scale model and the 3.3 m (130 in) diameter unit is presented in Fig. 4.

A blockage correction was applied to the results presented in Fig. 4 for the larger turbine as the wind-tunnel employed was of the enclosed working-section type. The results for the small model were not corrected for blockage as the model turbine represented only a 5% blockage in an open-jet wind tunnel. It can be seen from Fig. 4 that the maximum power coefficient obtained with the larger unit was 0.37, a value which is approximately 20 to 30% greater than the maximum power coefficients of 0.28 to 0.31 quoted in the literature as applicable to American multi-bladed wind-turbines commonly used for water pumping duties (Bragg and Schmidt, 1979; Eldridge, 1975).

Other aspects of delta-turbine performance, for example maximization of output when driving an irrigation pump and also arrangements for overspeed control, have been considered previously (Kentfield, 1978; Kentfield, 1979).

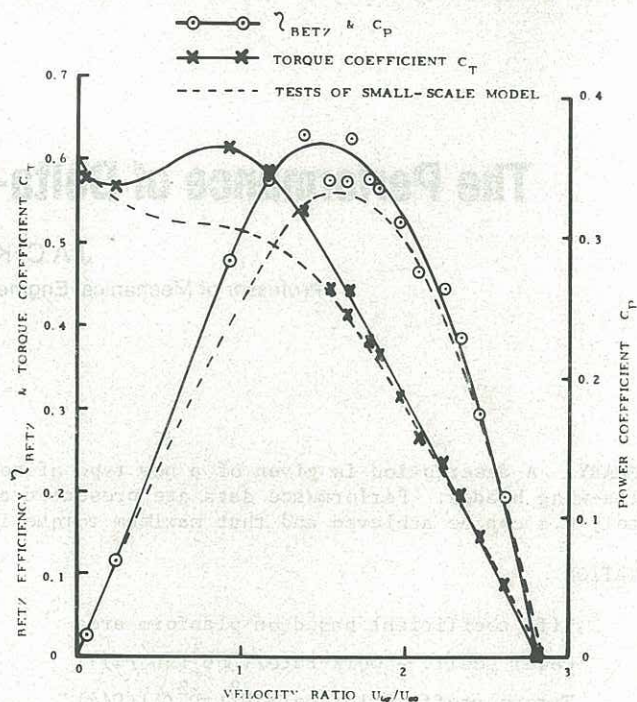


Figure 4 Results of wind-tunnel test of a 3.3 mm (130 in) diameter delta-turbine

### 4 INFLUENCE OF REYNOLDS NUMBER

An important by-product of wind-tunnel testing applied to wind-turbines is the quantification of the influence of Reynolds number on machine performance. For the case of the delta-turbine no prior data were available to serve as a guide to formulating a satisfactory Reynolds number correlation. Information relating to a Reynolds number effect can be deduced from Fig. 4 but this merely relates to the two sizes of machine tested. The problem is further complicated because the wind-tunnel normally available to the writer only permits tests to be conducted at low Reynolds numbers.

In an attempt to resolve this matter tests were carried out on a single, flat-plate, sharp-edged delta-wing at low Reynolds number. The aspect ratio of the model wing was chosen to be 2.0 as data were available in the literature (Hoerner and Borst, 1975) for a similar wing operating at a Reynolds number, based on mean chord, of  $3 \times 10^6$ . The results of tests conducted by the writer at a Reynolds number of  $9.8 \times 10^4$  are compared with those applicable to a Reynolds number of  $3 \times 10^6$  in Fig. 5. It can be seen that the lift curve slope,  $dC_L/d\alpha$ , is increased by approximately 10%. Drag data were not available for the high Reynolds number case but this is not viewed as a serious omission for a flat-plate delta since, to a first approximation ignoring skin friction, it is easy to show that;  $\text{drag} = \text{lift} \tan \alpha$ , hence knowledge of  $C_L$  versus  $\alpha$  is adequate to allow the drag to be estimated. It can hence be shown that the power and torque coefficients are substantially directly proportional to  $C_L$  when all other parameters are prescribed. The influence of Reynolds number should, therefore, be directly proportional to the variation of  $C_L$  with Reynolds number.

Points representing the results displayed in Fig. 5 have been added, as crosses, to Fig. 6 a plot of maximum power coefficient versus Reynolds number based on free stream conditions and mean blade chord. The difference between free-stream and relative velocity was negligible and was, therefore, ignored in transposing the results of the single-wing tests from Fig. 5 to Fig. 6. The cross corresponding to a



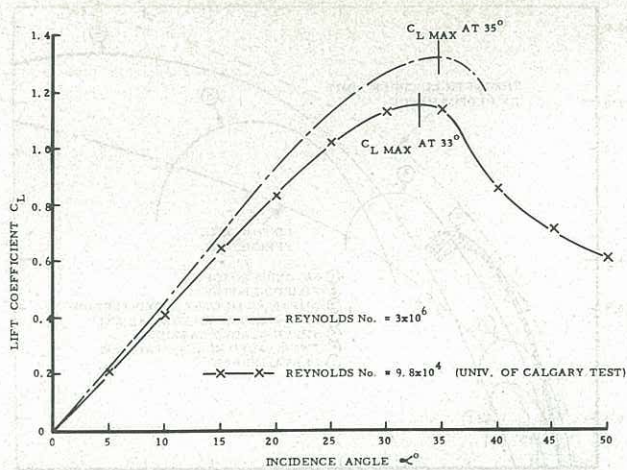


Figure 5  $C_L$  versus  $\alpha$  for sharp-edged delta wings of aspect ratio 2.0

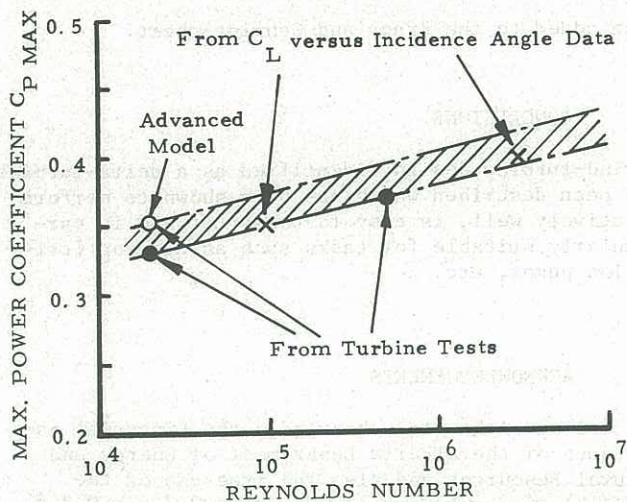


Figure 6 Maximum power coefficient versus Reynolds number

Reynolds number of  $9.8 \times 10^4$  was placed on the straight line joining the two turbine based test points: the second cross for a Reynolds number of  $3 \times 10^6$  was found to lie on an extension of this straight line. The lower curve of Fig. 6 indicates that a power coefficient of about 0.4 should be achievable with large turbines based on the geometry shown in Fig. 2 and 3. A result obtained from wind-tunnel tests of a small scale "fine-tuned" version of the turbine contributes the single data point on the upper curve of Fig. 7 which has been drawn parallel to the relatively definitive lower curve.

## 5 DEVELOPMENT POTENTIAL

An attempt was made to establish the development potential of delta-turbines using both theoretical analysis and experiment.

### 5.1 Potential Based on Performance Predictions

Assessments of performance potential were made utilizing a single-blade based performance prediction procedure described elsewhere (Kentfield and Norrie, 1977) extended to include an inflow-factor effect to account for reduction of the free-stream velocity from  $U_\infty$  to  $U'_\infty$  close to the rotor due to the rotor. The inflow factor employed, which was of a semi-empirical nature, took the form:

$$\frac{U'_\infty}{U_\infty} = \left[ 1 + \frac{m(1+j)}{\text{CONSTANT}} \left( \frac{U_\omega}{U'_\infty} \right)^2 \right]^{-1} \quad (1)$$

Equation 1 essentially implies that the inflow velocity defect is directly proportional to the product of the blockage,  $m(1+j)$ , and the square of the velocity ratio  $U_\omega/U'_\infty$ . The latter term is approximately proportional to the momentum of the flow entering the blading. The constant in equation (1) was evaluated from correlation of theory with experiment and was found to be approximately 30 for delta-turbines.

Results of evaluations made using the previously referred to theory, extended to take the inflow factor into account, are shown in Fig. 7. As can be seen from Fig. 7 the agreement between theory and experiment is fairly close. Extension of the predictions to other cases implied that, as might be expected, the delta-turbine concept is best suited

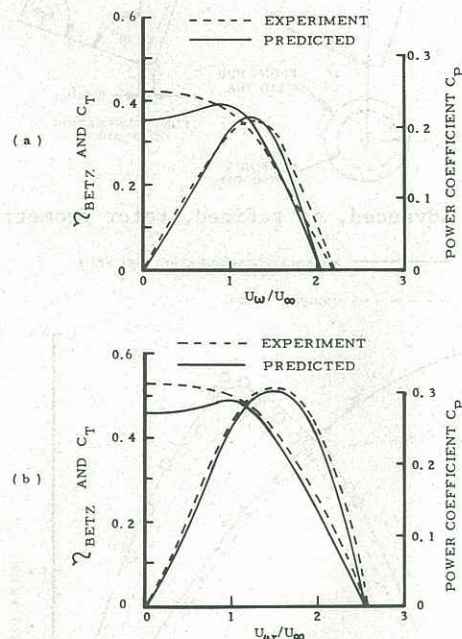


Figure 7 Comparison of predicted and experimental performances

(a) Without flaps

(b) Flaps lying parallel to rotor disc

for slow to medium velocity ratio operating conditions and also it should be possible to obtain an increase in  $C_P$  by using a stagger angle greater than  $50^\circ$  but only by sacrificing the attainment of maximum torque at zero speed.

### 5.2 Fine-Adjustment of Rotor Geometry

An experimental "fine-tuning" process was carried out on the basic blade geometry illustrated in Fig. 2 and 3 in an effort to obtain an improved performance without sacrifice of geometric simplicity or maximum torque at zero rotor speed. The configuration shown in Fig. 8 was finally arrived at after much experimentation. The main changes are an increase in the aspect ratio of the delta-wing surfaces and an increase in flap chord. The latter change was necessary to maintain maximum torque at zero speed. The only structural disadvantage is a slight increase in total blade area relative to the configuration shown in Fig. 2 and 3 resulting in an increase of  $m(1+j)$  from 0.55 to 0.60.

The corresponding improvements in performance are displayed in Fig. 9. Presumably the advanced configuration can be expected to respond to changes of Reynolds number as implied by the upper curve of Fig. 6. This in turn suggests that a power coefficient of 0.4 should be achievable in steady winds of about  $7 \text{ ms}^{-1}$  ( $15 \text{ mile h}^{-1}$ ) with a rotor of about



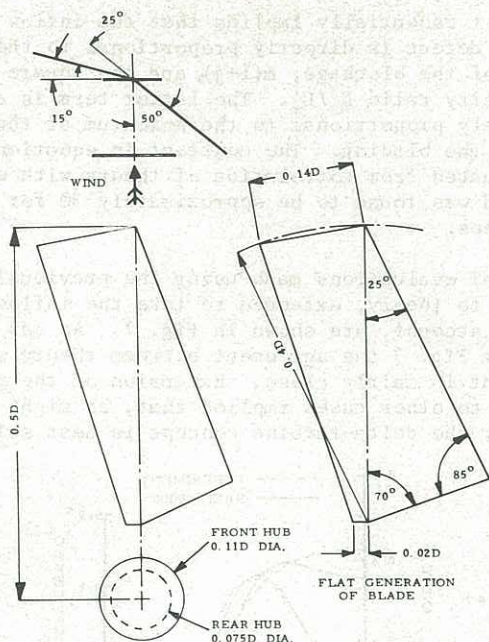


Figure 8 Advanced, or refined, rotor geometry

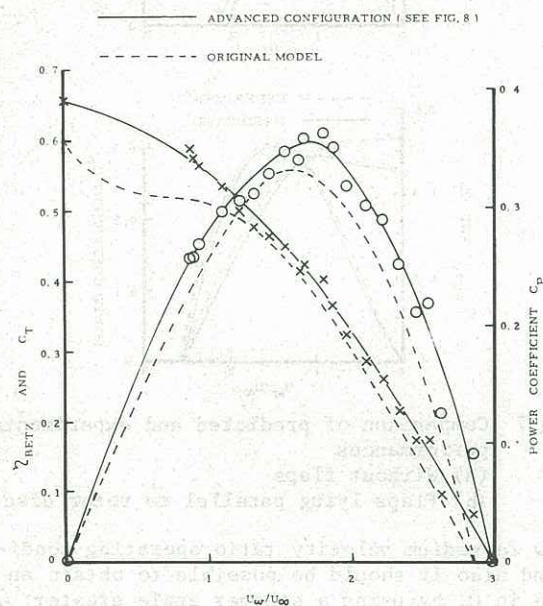


Figure 9 Comparison of performances of original and advanced versions of model rotors

6 m (20 ft) diameter.

## 6 COMPARISON WITH OTHER TURBINES

A comparison of the performance of delta-turbines with common types of wind-turbine on the power coefficient versus velocity ratio plane is available (Kentfield and Norrie, 1977). An alternative comparison on a basis suggested by Bragg and Schmidt (Bragg and Schmidt, 1979) is presented in Fig. 10. Here the abscissa is also velocity ratio but the ordinate is a parameter termed the power specific speed ( $\Pi$ ). When  $\Pi$  is referred to the turbine rotor speed Bragg and Schmidt showed that  $\Pi = C_p(U_w/U_\infty)^2$ . The merit of this method of performance comparison relates to the selection of a turbine based on a desired tip-speed ratio  $U_w/U_\infty$ . For a prescribed value of  $U_w/U_\infty$  the preferred machine is that which approaches most closely the dotted curve representing the ideal propeller turbine performance. The chain-dotted line corresponds to a power coefficient of 0.1. A band representative of the performance of delta-turbines has

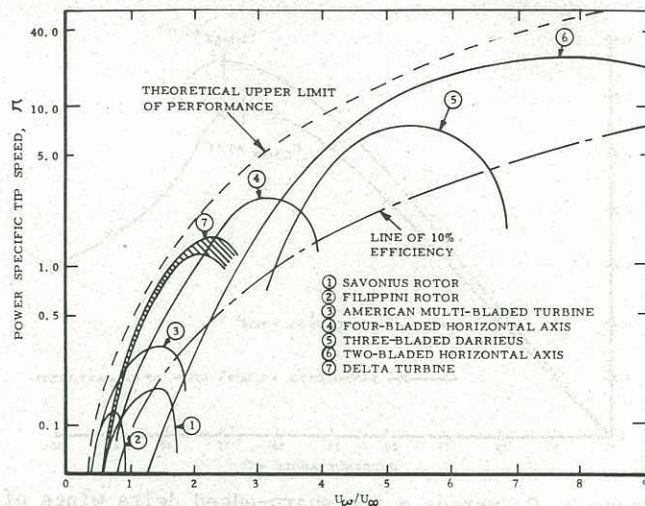


Figure 10 Wind-turbine performance comparison

been added to the Bragg and Schmidt chart.

## 7 CONCLUSIONS

A wind-turbine design, identified as a delta-turbine has been described which has been shown to perform relatively well, is easy to construct and is particularly suitable for tasks such as driving irrigation pumps, etc.

## 8 ACKNOWLEDGEMENTS

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