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THE NACA 0018-64 AEROFOIL AT LOW REYNOLDS NUMBERS WITH APPLICATION TO VERTICAL AXIS WIND TURBINES - INCLUDING TURBULENCE STIMULATION

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ABSTRACT

The structural requirements for an aerofoil with generous thickness aft of mid-chord have led to the choice of the 0018-64 profile for an experimental vertical axis wind turbine. Data on its behaviour at the low Reynolds numbers typical of wind turbines is not readily available in the literature.

An investigation of the lift, drag and boundary layer behaviour at Reynolds numbers 140,000 and 300,000, covering a 360 degree variation in attack angle is presented. Also presented is a method for modifying the flow characteristics at low Reynolds number using surface treatment to stimulate a turbulent boundary layer close to the leading edge.

INTRODUCTION

The study of the performance of a NACA 64-0018 aerofoil at low Reynolds numbers (Rn) was initiated in order to obtain data relevant to the use of the blade on a prototype Vertical Axis Wind Turbine (VAWT) built at the University of Melbourne, as well as in the computer modelling of this turbine.

The 0018-64 was used mainly because the shifting of the maximum thickness back to 40% chord allowed the blade to be extruded with a cavity sufficient to house span-wise mechanisms.
The blade is also thicker than more popular VAWT aerofoils, however experimentation (Angell, Musgrove and Galbraith, 1988) indicates improved performance of thicker sections at low tip speed ratios (higher wind speeds relative to the turbine angular velocity), as well as the cost and design advantages of the increased strength.

Only a limited amount of data is available for aerofoils at low Rn, though the field has been subject to renewed interest with application to remotely piloted vehicles, gliders, ultralights, man-powered and high altitude aircraft, as well as the advent of modern wind turbines. However it was demonstrated by Pinkerton (1938) that the performance of aerofoils rapidly deteriorates with decreasing Rn if the Reynolds number is below about 1.5 million. The occurrence of a separation bubble close to the leading edge has a significant role in this deterioration.

Much of the early data that does exist, including Pinkerton's paper, is of limited application due to the use of high turbulence wind tunnels. Turbulence was encouraged in the belief that it simulated behaviour of higher Rns, termed, 'effective Reynolds number'.

Consequently the reasons for testing the actual aerofoil are several-fold:
(1)The absence of applicable data for the 0018-64;
(2)The prototype VAWT operates in the Rn region of 50,000 - 1.5 million, where the lift and drag characteristics are strongly Rn dependant;
(3)The absence of analyses to adequately model this Rn region;
(4)A requirement for a comparative study of pressure distributions (due to the boundary layer dependence upon surface finish);
(5)A 360° characteristic is needed for VAWTs since the attack angle relative to the apparent wind may vary over 360° in one revolution of the rotor.

Following tests on the aerofoil with a smooth finish, a study of the effects of turbulence stimulation was also undertaken.

AEROFOIL AND EXPERIMENTAL METHOD

All experiments were carried out in the large closed return wind tunnel in the Walter Bassett fluids laboratory of the University of Melbourne.

The extruded aluminium blades for the wind turbine had a chord of 0.18 metres. Of this, a 1.6m section was pressure tapped with two identical sets of 35 orifices (of diameter 0.75mm) normal to the surface with an increased concentration close to the leading edge (see figure 1). Both surfaces were improved with the use of a fine grain emery paper.

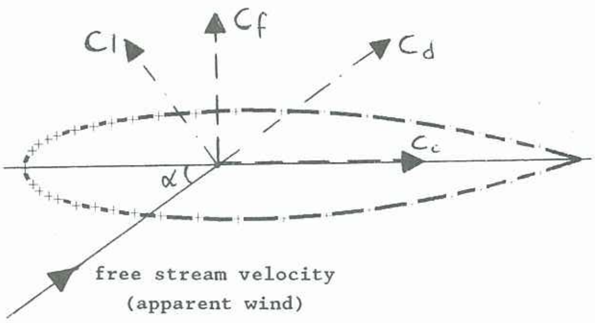

Figure 1: NACA 0018-64 profile with pressure tappings (+).

The advantages of using two sets of pressure tappings were perceived to be: (1) Validation of the method of manufacturing pressure tappings in case of possible differences due to positioning inclination relative to the surface, or local abnormalities; (2) Information by comparison as to the precision of pressure distributions; (3) Comparative side by side experiments using different surface treatments.

The pressure tappings were staggered at an angle of about 35° relative to the chord line to avoid disturbance of downstream pressure measurements. Also the two series were separated with a boundary layer fence to prevent propagation of stall and span-wise flow along the blade.

The aerofoil spanned the test section completely. An inclinometer was used to measure relative angles and so find the angle of attack (α).

An integrating drag comb was placed on a traverse in the wake of the aerofoil. The use of this device to obtain drag measurements is detailed by Young (1938). The comb could only be used with attached flow where the wake was sufficiently narrow to be contained within the comb. However, when an aerofoil has stalled it is reasonable to treat it as a bluff body and calculate the drag from pressure measurements.

The blade tappings and integrating comb tubes were connected to a bank of methanol manometers. Each manometer also had a connection to the total and static tappings of the wind tunnel, allowing pressure coefficients (Cp) to be calculated directly without reference to the absolute dynamic head or manometer inclination.

RESULTS

0018-64 Aerofoil Through 200 Degrees of Rotation

The lift and drag were calculated in two stages by integration of Cp around the blade to obtain the coefficients of chord-wise (Cc) and flap-wise (Cf, normal to the chord) forces, followed by transformation to the coefficients of lift (Cl) and drag (Cd) using α. Figures 2 and 3 show the variation in lift and drag at Rn=300,000. Throughout the region of separated flow the lift and drag have a simple behaviour. As discussed by Lock and Townsend (1924) the general nature of this distribution is the same for all aerofoils as they behave much like a flat plate, however the Cd is markedly higher than for Rns above about 2 million. This result is consistent with previous work (e.g. Khoo and Graham, 1988).

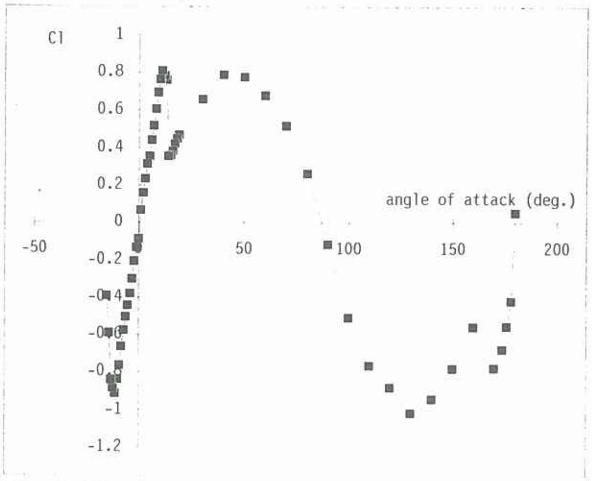

Figure 2: Cl vs α through 200°, Rn=300,000.

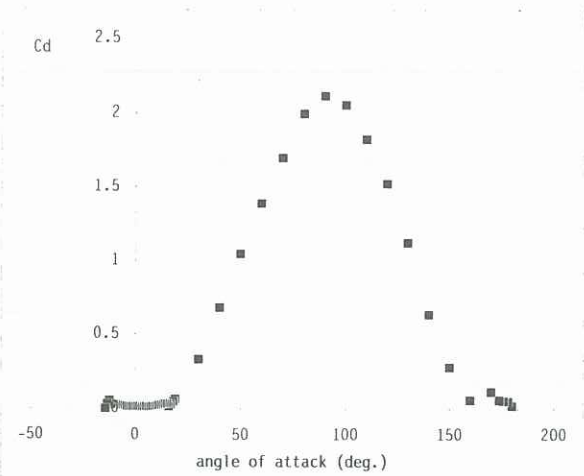

Figure 3: Cd vs α through 200°, Rn=300,000.

The aerofoil has attached flow between -12° and +12°, as well as 170° to 190°. In figures 9 through 14 the lift and drag for attached flow at the two Rns are shown in more detail and it can be seen that the aerofoil stalls sharply at a little over 12°. The process of stall can be seen via Cp distributions in figure 4. A significant factor in the performance of the aerofoil is the occurrence of a separation bubble between 6° and stall. Figures 5 and 6 show the growth of this bubble at the higher and lower Rns. Significant points to note are the proximity of the separation to the leading edge and the increase in the span-wise length of the separation bubble with decreasing Rn.

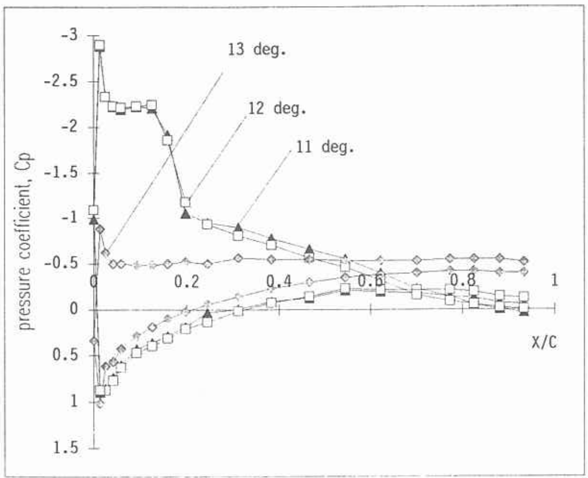

Figure 4: Stall of aerofoil with smooth surface, Rn=140,000.

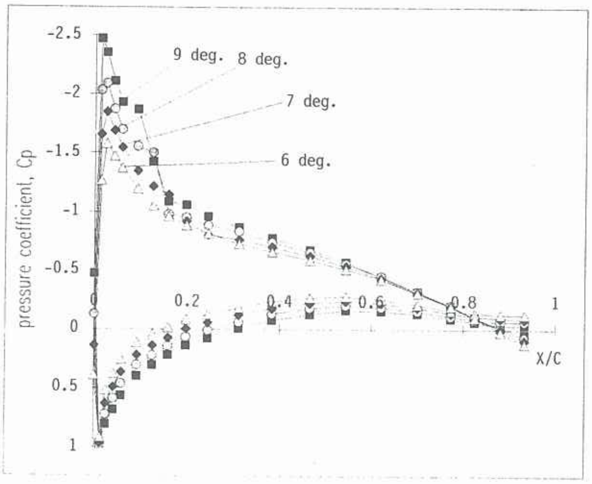

Figure 5: Growth of separation bubble, Rn=300,000.

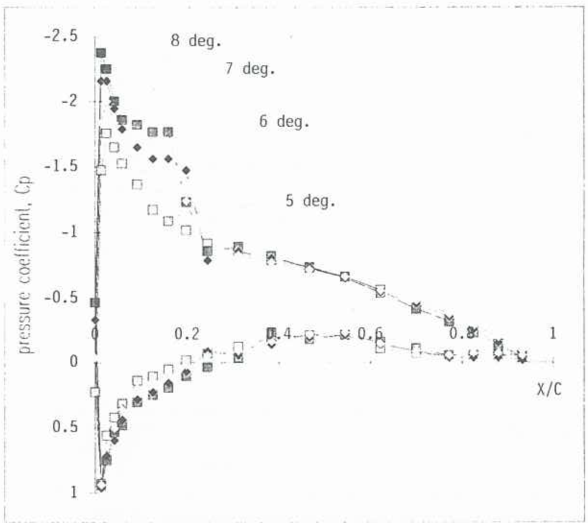

Figure 6: Growth of separation bubble, Rn=140,000.

Comparison of Leading Edge Trip Strip Data

Typically strips with a rough surface (sand, grit or other protrusion) are applied to the top and bottom surfaces of aerofoils to cause a well defined transition of the boundary layer from laminar to turbulent. A series of experiments were undertaken to use trip strips to generate a turbulent boundary layer able to adhere to the aerofoil surface though the strong adverse pressure gradient following the suction peak.

Due to the proximity of the start of separation to the leading edge, a single strip was proposed. The use of leading edge trip strip has been considered previously in the work of Bloch and Mueller (1986) applied to a non-symmetric (Wortman) section. The advantages of a single strip for a symmetric section where positive and negative angles of attack are required are two-fold: (i) At low α where separation does not occur, the strip is at, or close to, the stagnation point, in low velocity flow and therefore has a smaller contribution to surface drag; (ii) As α increases the strip only trips the boundary layer on the surface prone to separation, and the other surface is left laminar until natural transition takes place.

The turbulence stimulating effects of such strips are largely width independent. Several tests were carried out with differing widths and a 2mm strip was selected, equivalent to 2-3 grit diameters. The important aspect of such strips is the depth of penetration into the boundary layer and with lower dynamic pressures the height of strip required increases. Pope and Harper (1966) suggest a strip height of the order of 1mm (based on the positioning of the strip relative to the leading edge and the Rn).

Aluminium oxide grit (Carborundum cubical blocky) was used and it should be noted that such grit has an associated distribution due to the sieving process with approximately 70% particles within 20% of the quoted median. Figure 7 shows the effect on the pressure distribution, at $\alpha=10°$, of trip strips with Carborundum numbers 20, 24, 36, 46, corresponding to median grit sizes of 1mm, 0.75mm, 0.53mm, 0.39mm. Also in figure 7 is a theoretical Cp distribution found using Theodorsen's (1931) conformal mapping for non-viscous flow (unmodified).

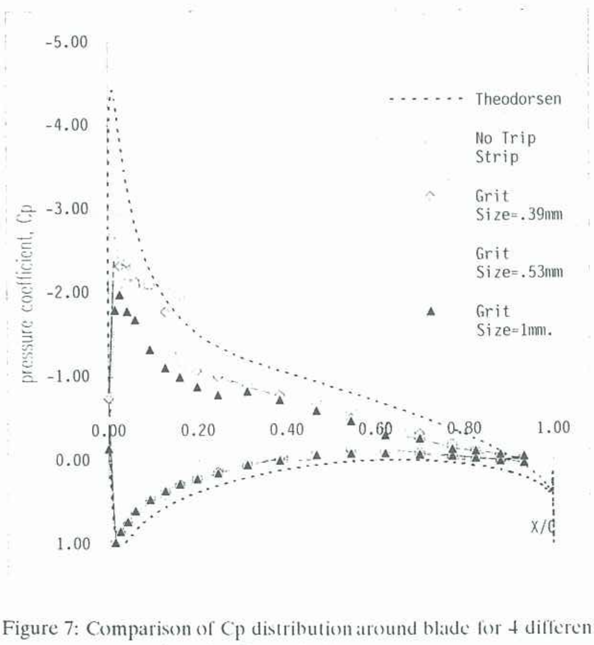

Figure 7: Comparison of Cp distribution around blade for 4 different trip strips. Rn=140,000.

Note that the 1mm grit causes severe reductions in circulation. Reducing the grit size increases the circulation until with the 0.39mm grit the Cp distribution tends towards that of flow with a separation bubble.

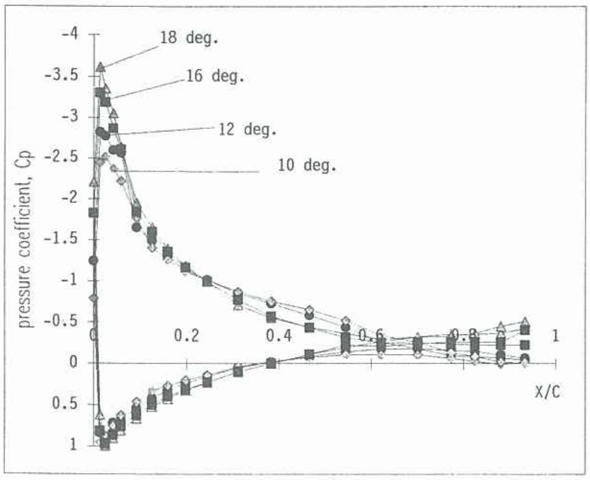

Figure 8: Graduation of stall with 0.53mm grit strip, Rn=140,000.

In figure 8, at the lower Rn, it can be seen that the process of stall is graduated with the application of the strip. The front of the aerofoil remains in attached flow and trailing edge separation slowly moves forward as α is increased. In Figures 9, 10 and 11 the coefficients of lift and drag, and the and lift/drag ratio are plotted against α for 0.75mm and 0.53mm grit as compared with the smooth aerofoil. Here the delay of stall to greater α is manifest in the maintenance of high lift coefficients to higher α. At the low Rn there is a significant broadening of the Cl/Cd curve corresponding to an extension of the working α from 12° to 16°.

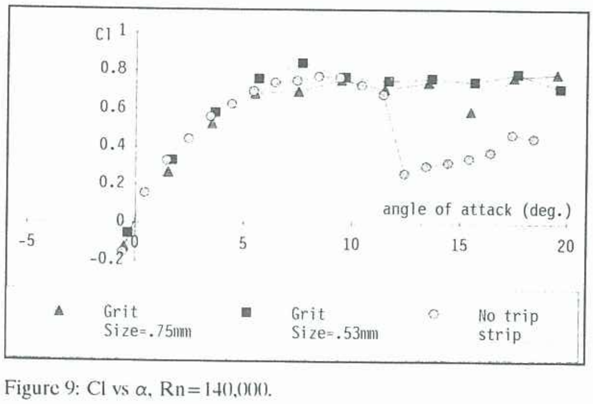

Figure 9: Cl vs α, Rn=140,000.

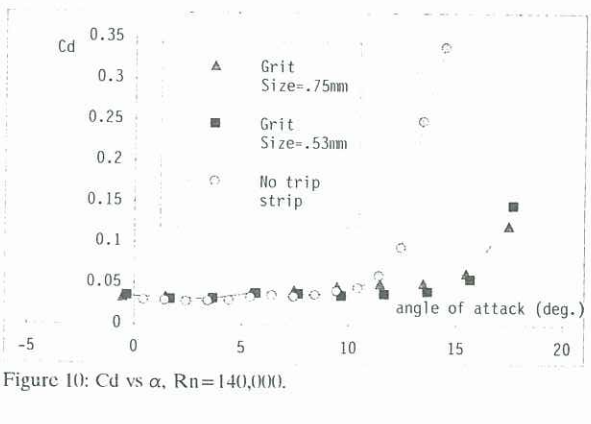

Figure 10: Cd vs α, Rn=140,000.

Note that only with the 0.53mm grit were the increased drag and reduced circulation due to strip height minimised sufficiently to give Cl/Cd performance comparable with the smooth blade.

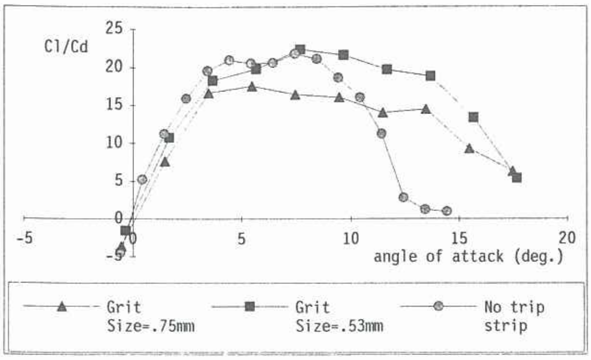

Figure 11: Cl/Cd vs α, Rn=140,000.

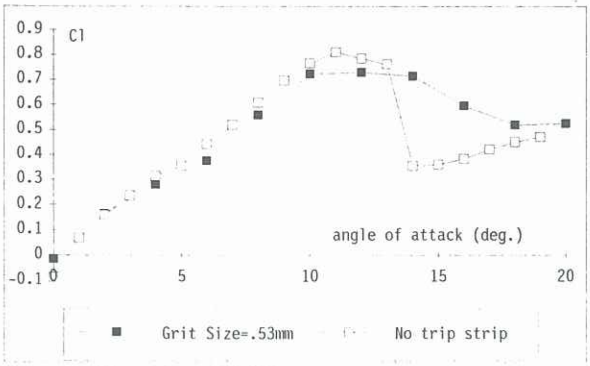

Figure 12: Cl vs α, Rn=300,000.

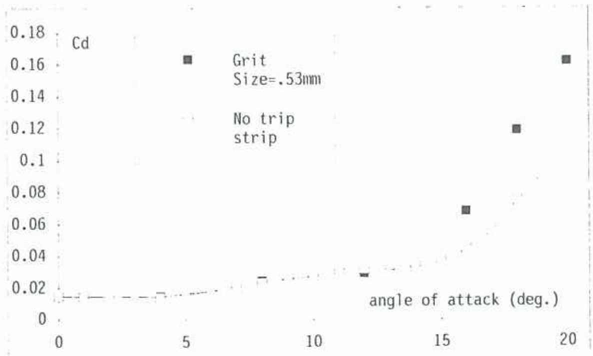

Figure 13: Cd vs α, Rn=300,000.

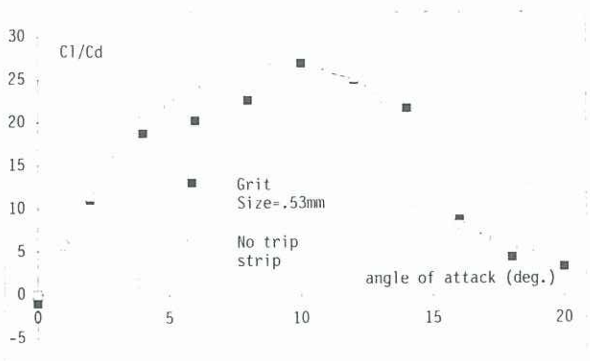

Figure 14: Cl/Cd vs α, Rn=300,000.

Figures 12, 13 and 14 show the results of using the 0.53mm grit strip at the higher Rn. Here the effect on lift and drag with the strip penetrating much more deeply than required to cause transition is seen. The resulting Cl/Cd shows a slightly lowered performance, however as with the result at the lower Rn, the working range of the aerofoil is increased by about 2°.

CONCLUSIONS

(1) With separated flow the aerofoil blade has a predicatble lift and drag behaviour through 360° rotation.

(2) The main gains in using a trip strip are a broadening of performance curve to higher α and a smoothening of the stall characteristics. However no substantial increase in maximum Cl/Cd is achieved despite the removal of the separation bubble.

The Cl/Cd extension to higher α has application to Vertical Axis Wind Turbines working at low tip speed ratios.

Smoothening of the stall characteristic is also relevant to stall regulated devices where the sudden loss of lift due to rapid growth of the separation bubble during dynamic stall is a significant problem.

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