WIND ENERGY
Wind Energ., **2**, 125–136 (1999)

Research Article

Aerodynamic Effects of Leading-edge Tape on Aerofoils at Low Reynolds Numbers

Philippe Giguère* and Michael S. Selig, Department of Aeronautical and Astronautical Engineering, University of Illinois at Urbana-Champaign, 306 Talbot Laboratory, 104 South Wright Street, Urbana, IL 61801, USA

Key words:
small wind turbines; aerofoil aerodynamics; leading-edge tape

A systematic wind tunnel study was conducted to gain an understanding of the aerodynamic effects of leading-edge tape, which is typically used on small wind turbines as a protection from blade erosion. The wind tunnel tests included lift and drag measurements over the Reynolds number range from 150,000 to 500,000. In addition, flow visualization experiments were carried out. Various tape configurations were tested on five aerofoils, namely the BW-3, FX 63-137, S822, SG6042 and SG6051. Although the magnitude of the aerodynamic effects of the tape was aerofoil-dependent, it was found that extending the tape beyond 5% chord and staggering multiple tape layers were most beneficial in minimizing the loss in aerofoil performance. The practical significance of the results on wind turbine performance is discussed. In particular, the data for the SG6042 aerofoil were used to quantify the effects of the tape on the power coefficient of small variable-speed wind turbines. Overall, the different tape configurations tested reduced the power coefficient by no more than 2·1%. From the trends shown, however, larger reductions in power coefficient should be expected for larger wind turbines than those considered, particularly if two layers of tape are used. In light of this study, guidelines for optimum application are suggested. Copyright ©1999 John Wiley & Sons, Ltd.

Introduction

Wind turbine blades are exposed to various abrasive airborne particles that erode their surface, particularly at the leading edge. Over time, these airborne particles, such as sand, can cause significant damage that reduces aerodynamic performance. The application of tape is a commonly used low-cost method of protecting the blades from leading-edge erosion. In addition, leading-edge tape that provides a slick surface reduces the accumulation of insect debris or other contaminants. Even though leading-edge tape is often used, especially on small wind turbines, there is only limited literature on its aerodynamic effects, and no application strategies have been proposed.

The only documented results on the aerodynamic effects of leading-edge tape appear to be those obtained during the development of the North Wind 4 kW turbine.[1] In brief, wind tunnel test results for a Göttingen 797 aerofoil at a Reynolds number of 350,000 indicated large drag and lift penalties when the tape ended at 10% chord, and extending the tape to 20% chord significantly reduced those penalties in aerofoil performance. These results documented by Coleman and Mayer[1] provided motivation to further investigate the aerodynamic effects of leading-edge tape in detail. Additional motivation arose from the current development of four turbines in the 8–40 kW range,[2] which are likely to use leading-edge tape.

*Correspondence to: Philippe Giguère, National Renewable Energy Laboratory (NREL), 1617 Cole Boulevard, MS 3811-NWTC, Golden, CO 80401, USA.

Contract/grant sponsor: National Renewable Energy Laboratory; Contract/grant number: XAF-4-14076-03.

Revised 25 May 1999
Accepted 1 July 1999

In an effort to understand the aerodynamic effects of leading-edge tape and provide application guidelines, a systematic wind tunnel study was conducted. This article presents lift and drag data for various tape configurations, aerofoils and test Reynolds numbers as well as results from flow visualization experiments. An overview of the flow phenomena related to the aerodynamic effects of leading-edge tape concludes this introduction before the wind tunnel facility and the testing approach are described. The results obtained are then presented and discussed in terms of both aerofoil and wind turbine performance. Finally, the application guidelines are presented as part of the conclusions.

Flow Phenomena

The presence of leading-edge tape on an aerofoil alters the natural development of the boundary layer owing to the disturbance caused by the backward step at the edge of the tape. There is a small separated region (as will be shown) with subsequent step growth in the momentum thickness behind the tape edge that results in drag, which is referred to as device drag. For laminar boundary layers, this disturbance initiates the transition process, similar to that of mechanical turbulators (e.g. trips) as transition has been shown to be triggered at or near the trailing edge of the trip.[3,4] The aerodynamic effects of 'plain trips' (strips of tape) are, however, not identical to those of leading-edge tape, probably because of their forward step.[5]

The blades of small wind turbines typically operate at low Reynolds numbers where boundary layers are relatively thick. Therefore tape of a given thickness is likely to cause less device drag than at higher Reynolds number, because a larger part or all of the tape edge can be submerged in the boundary layer. An important phenomenon at low Reynolds numbers is that laminar separation followed by transition and turbulent reattachment often occurs, resulting in a laminar separation bubble. Such laminar separation effects, which result in increased drag (bubble drag), are aerofoil-dependent and are typically dominant on conventional aerofoils for Reynolds numbers below 500,000. A summary of the underlying characteristics of low-Reynolds-number aerofoil aerodynamics can be found in Reference 6.

Trips have been used to trigger early transition to turbulent flow, thereby avoiding the formation of a laminar separation bubble and its associated drag penalty.[4] The idea is to trigger transition with the smallest trip possible to minimize device drag. Figure 1(a) shows the beneficial effect of early transition on the drag polar of an aerofoil with a laminar separation bubble (the 'high-drag knee' is indicative of the

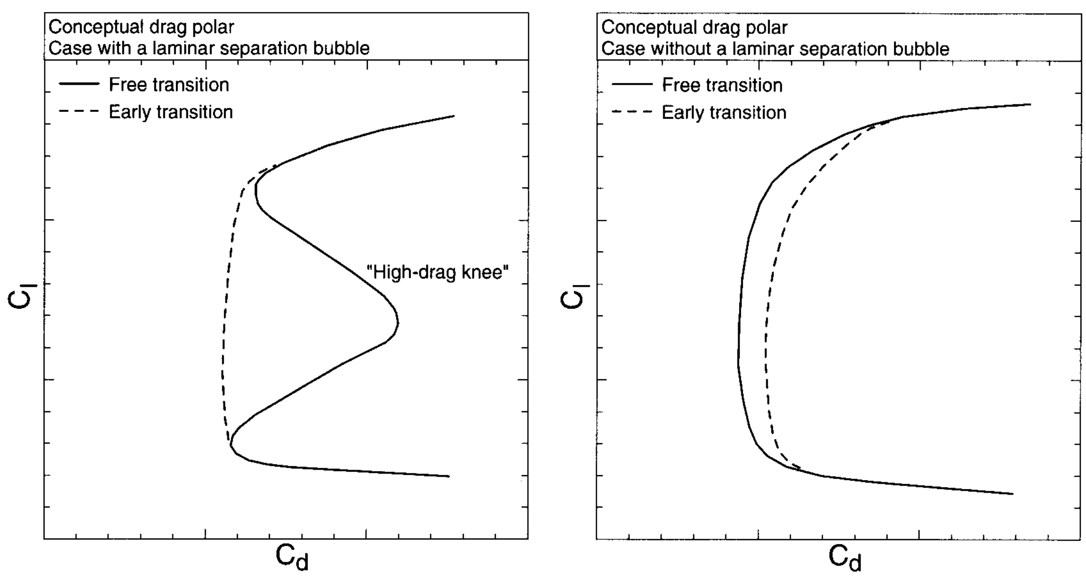

Figure 1. Conceptual effect of early transition on the drag polar of (a) an aerofoil with a laminar separation bubble and (b) an aerofoil without a laminar separation bubble

presence of a laminar separation bubble on the aerofoil). In contrast, Figure 1(b) indicates that early transition on an aerofoil without a laminar separation bubble is detrimental because of the longer run of turbulent flow, which increases skin friction drag, and the added drag from the mechanism triggering transition (trip, tape, etc.). Therefore the overall effect of a trip or leading-edge tape at low Reynolds numbers depends on the trade-offs between bubble, device and skin friction drag for each particular aerofoil.

Wind Tunnel Facility and Testing Approach

All experiments were conducted in the University of Illinois at Urbana-Champaign (UIUC) subsonic wind tunnel, which has a nominal test section 0·857 m (2·81 ft) high and 1·219 m (4 ft) wide. The test set-up depicted in Figure 2 was used for this study.[7,8] As shown in Figure 2, two 1·829 m (6 ft) long Plexiglass splitter plates are inserted 0·854 m (2·8 ft) apart into the test section to isolate the aerofoil models from the support hardware and the tunnel side wall boundary layers. The 0·305 m (1 ft) chord aerofoil models are inserted horizontally between the splitter plates with nominal gaps of 1–2 mm (0·040–0·080 in). For this test set-up the upper end of the test Reynolds number range is 500,000 and the turbulence intensity of the tunnel with an empty test section is less than 0·1%.[7] Most of the tests were conducted at a Reynolds number of 300,000, but Reynolds numbers of 150,000 and 500,000 were also considered.

The lift was measured using a strain gauge load cell, and the drag was determined from the momentum deficit method. To account for the spanwise drag variations at low Reynolds numbers,[9] the drag was obtained from the average of four equidistant wake surveys over the centre 0·229 m (9 in) of the model span. Data files presenting the drag coefficient computed from each of the four wake surveys are documented at http://www.uiuc.edu/ph/www/m-selig. The overall uncertainty in both the lift and drag measurements was estimated to be 1·5%.[7,8] All measurements were corrected for wind tunnel interference and circulation effects according to a method that has been validated with data from the NASA Langley Low Turbulence Pressure Tunnel.[10] For the flow visualization experiments the technique consisted of spraying fluorescent pigment suspended in mineral oil that was air-brushed onto the surface of the model. After sufficient wind tunnel run time (20–30 min), surface flow features could be seen under a fluorescent light.

3M® 8672 polyurethane tape, 0·2 mm (0·008 in) thick, was used in this study, as it is commonly used by small wind turbine manufacturers. As shown in Figure 3(a), the tape edge was positioned at either 5%,

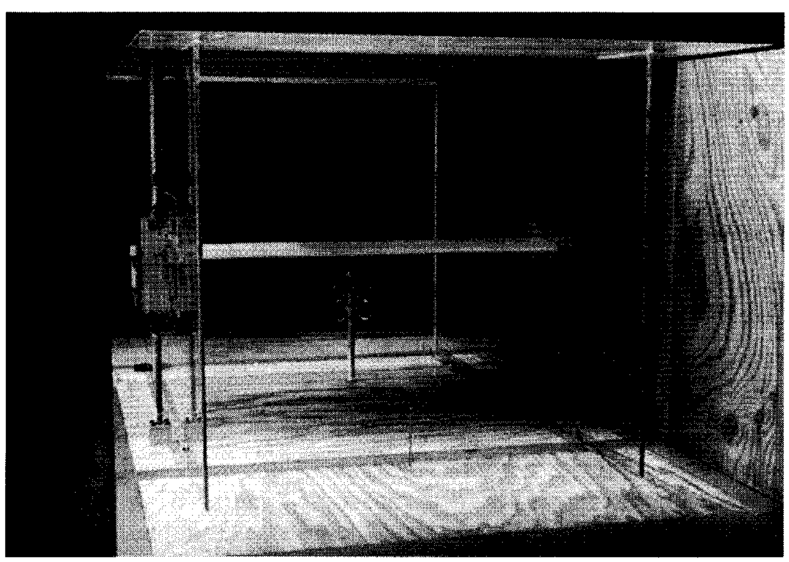

Figure 2. The UIUC subsonic wind tunnel set-up for low-Reynolds-number aerofoil testing

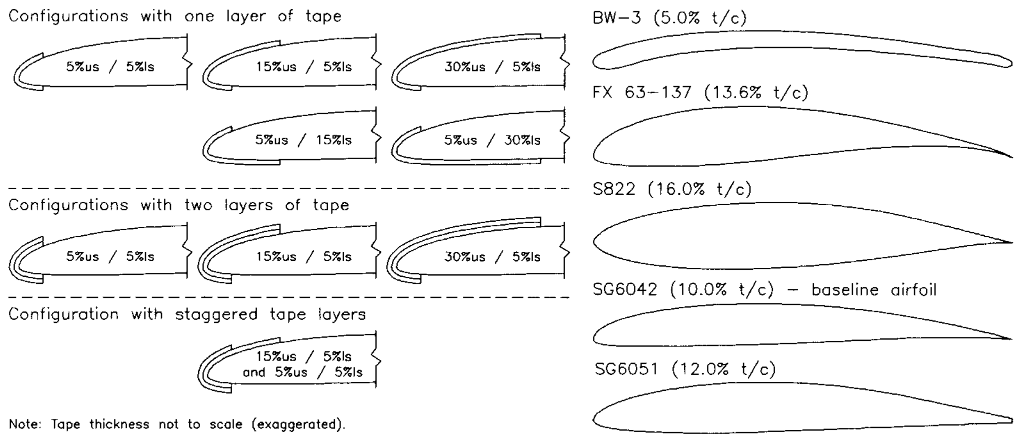

Figure 3. (a) Leading-edge tape configurations and (b) contours of aerofoils tested

15% or 30% on the suction and pressure surface. Configurations with two layers of tape were also tested to investigate what is typically used on the outboard portion of the blades where erosion is more severe. The tape was carefully applied to the models to avoid trapping air bubbles under the tape, as they would act as undesirable isolated roughness elements.

Most of the tests were carried out using the SG6042[8,11] aerofoil, which is depicted in Figure 3(b) together with the other four aerofoils considered in this study, namely the Bergey Windpower BW-3,[6,8] the Wortmann FX 63-137,[7] the NREL S822[6,7] and the SG6051.[12] These five aerofoils span a range of relative thicknesses and lift ranges that are representative of aerofoils that meet design requirements for both constant- and variable-speed wind turbines. Predicted pressure distributions for the aerofoils can be found in References 7 (FX 63-137 and S822), 8 (BW-3 and SG6042) and 12 (SG6051). Except for the FX 63-137, all these aerofoils were designed for wind turbine applications, and the SG6051 was also designed knowing that leading-edge tape would be used with it. In addition, these aerofoils are presently used on small turbines, with the exception of the relatively new SG6042 aerofoil.

The wind tunnel models were made of foam core covered with fibreglass. A coordinate-measuring machine was used to digitize the models.[7] The differences between the nominal and measured coordinates were calculated, allowing the computation of an average accuracy for each model (mean of the differences). These differences are almost always smaller than 0·8 mm (0·030 in) and the average accuracy is 0·4 mm (0·015 in) or better. Details of the models' accuracy, including plots of the differences between the nominal and measured coordinates, can be found in References 5 (all aerofoils), 8 (FX 63-137 and S822 aerofoils) and 9 (BW-3 and SG6042 aerofoils).

Results and Discussion

The results are presented and discussed in three sections, namely (1) flow visualization, (2) effects of the tape on lift and (3) effects of the tape on drag. The practical significance of these results is discussed separately. Additional results can be found in Reference 5.

Flow Visualization

The effect of leading-edge tape on the boundary layer development is depicted in Figure 4. This figure shows photographs of the fluorescent oil flow patterns on the suction surface of the SG6042 aerofoil at an angle of attack of 4° and a Reynolds number of 500,000 with and without leading-edge tape. (The angle of attack of 4° corresponds to the design lift coefficient of approximately 0·9, which is the lift coefficient for best lift-to-drag ratio of the SG6042 aerofoil.) Figure 4(a) shows that with no tape the natural transition to

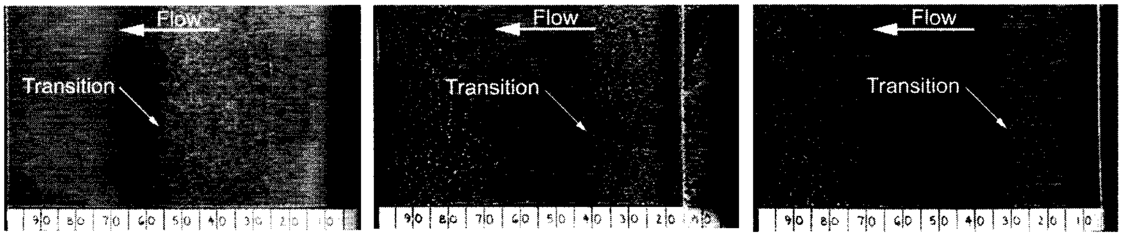

Figure 4. Oil flow visualization on the suction surface of the SG6042 aerofoil at an angle of attack of 4° and a Reynolds number of 500,000: (a) no tape; (b) tape to 15% chord; (c) tape to 5% chord

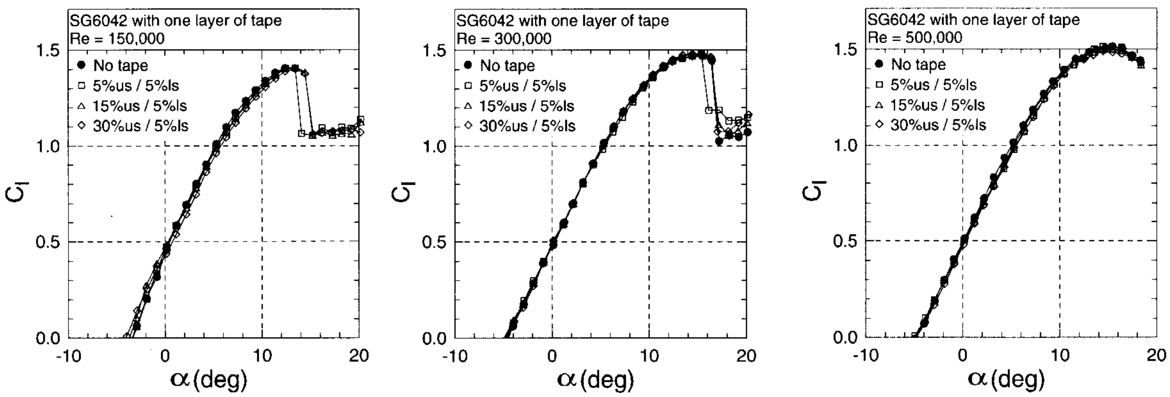

Figure 5. Lift curves showing the effect of the Reynolds number on the SG6042 aerofoil (one layer of tape): (a)Re = 150,000; (b)Re = 300,000; (c)Re = 500,000

turbulent flow occurs at approximately 55% chord. As expected, the tape caused early transition to occur, which is indicated in Figures 4(b) and 4(c). More precisely, transition took place at approximately 40% chord and 30% chord for the tape edge at 15% chord and 5% chord respectively. Based on the absence of a laminar separation bubble in Figure 4(a), there is a drag penalty associated with the tape. The longer run of turbulent flow results in an increase in skin friction drag, and the separated region behind the tape edge causes device drag. Extending the tape further downstream to match the natural transition location would likely reduce the drag penalty of adding the tape. Practically, however, the optimum tape configuration is one that minimizes both the loss in aerodynamic performance and the amount of tape needed.

Leading-edge Tape Effects on Lift

Figure 5 shows the effect of leading-edge tape on the lift characteristics of the SG6042 aerofoil with one layer of tape for the three Reynolds numbers considered in this study. For clarity, only the data for increasing angle of attack are shown. Note that the SG6042 aerofoil has a small stall hysteresis loop below a Reynolds number of 500,000 that was also present when tape was added.[5,8] The legend of Figure 5 and those of the drag polars to follow refer to Figure 3(a). These results are representative of the five aerofoils tested with one layer of tape. As shown in Figure 5, the overall effects of the tape on lift are small. Adding a second layer of tape was found to slightly increase the reduction in the lift curve slope.[5]

Leading-edge Tape Effects on Drag

Figure 6 presents drag polars and boundary layer development data for the SG6042 aerofoil at a Reynolds number of 300,000. More precisely, Figure 6(a) shows the effect of the tape edge location on the suction

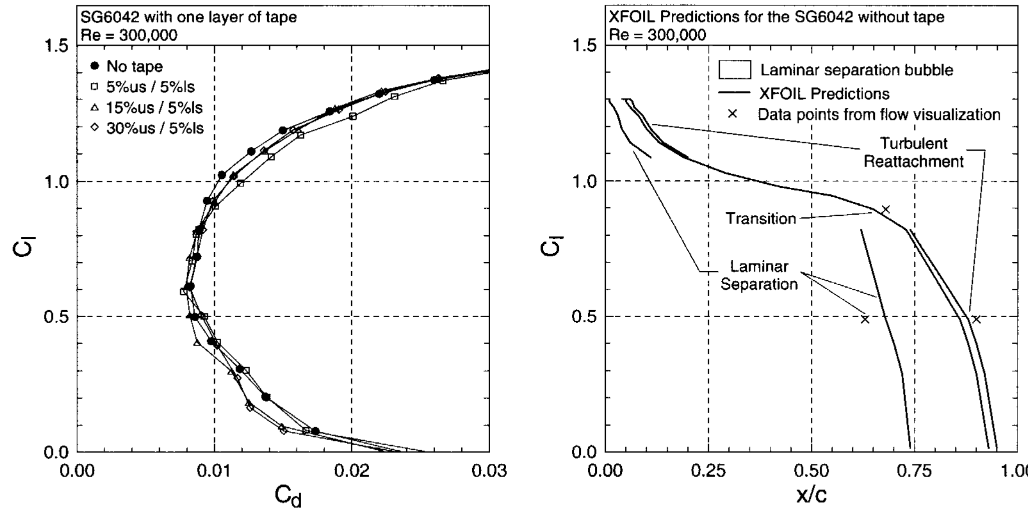

*Figure 6. (a) Drag polars showing the effect of varying the tape edge location (one layer of tape) on the suction surface of the SG6042 aerofoil and (b) corresponding XFOIL predictions for the boundary layer behaviour for the case without tape (*Re = *300,000)*

surface for one layer of tape, while Figure 6(b) presents the chordwise behaviour of the suction surface transition location and laminar separation bubble without tape. The boundary layer development data were obtained using the computer program XFOIL.[13] As shown in Figure 6(b) the XFOIL results are representative of results obtained from flow visualization experiments.[5]

The drag trade-off between bubble, device and skin friction drag is clearly illustrated in Figure 6. As expected, the drag reductions from the tape for lift coefficients below 0·8 shown in Figure 6(a) correspond to a lift range for which a laminar separation bubble is present on the aerofoil (Figure 6(b)). Above a lift coefficient of 0·8 the tape did not provide reduced drag, because there was either no laminar separation bubble or the bubble was within the area covered by the tape, thus limiting its impact on bubble drag. Extending the tape beyond 5% chord appears to be beneficial, as the two other configurations tested (15% and 30%) provided lower drag over most of the lift range. The increase in drag above a lift coefficient of 0·8 caused approximately a 4·5% decrease in the maximum lift-to-drag ratio, which is similar for the three tape configurations. Ending the tape at 5% chord and 15% chord, however, reduced the lift coefficient for best lift-to-drag ratio from 0·93 to 0·81.

The effect of tape ending location on the pressure surface of the SG6042 aerofoil was also investigated. The results showed that ending one layer of tape at either 5%, 15% or 30% chord yielded similar drag polars and lift curves.[5] Therefore the location of the tape edge on the pressure surface is not critical, which had to be expected from the favourable pressure gradient acting over that surface when generating positive lift. Accordingly, extending the tape to match the expected impingement limits on the pressure surface comes at no cost in aerodynamic performance.

The results of the experiments for the SG6042 aerofoil at a Reynolds number of 300,000 with two layers of tape are presented in Figure 7. Compared with the results for one layer of tape (Figure 6(a)), the drag polars shown in Figure 7(a) depict mainly larger drag penalties that resulted in a 10%–14% decrease in the maximum lift-to-drag ratio. The drag is slightly lower, however, for lift coefficients below 0·2, which is an indication of the magnitude of the bubble drag over that lift range. Again, ending the tape at 5% chord caused the largest increase in drag for the three tape configurations. Owing to the larger drag penalty of two layers of tape, extending the tape beyond 5% chord should be particularly favoured for the outboard blade section. Practically, however, it appears to be a good application strategy to stagger tape layers, as the results of Figure 7(b) suggest. This figure shows that the drag polar of the stagger case (see Figure 3(a)), which has its second layer ending at 5% chord, is similar to the results for one layer ending at 5% chord

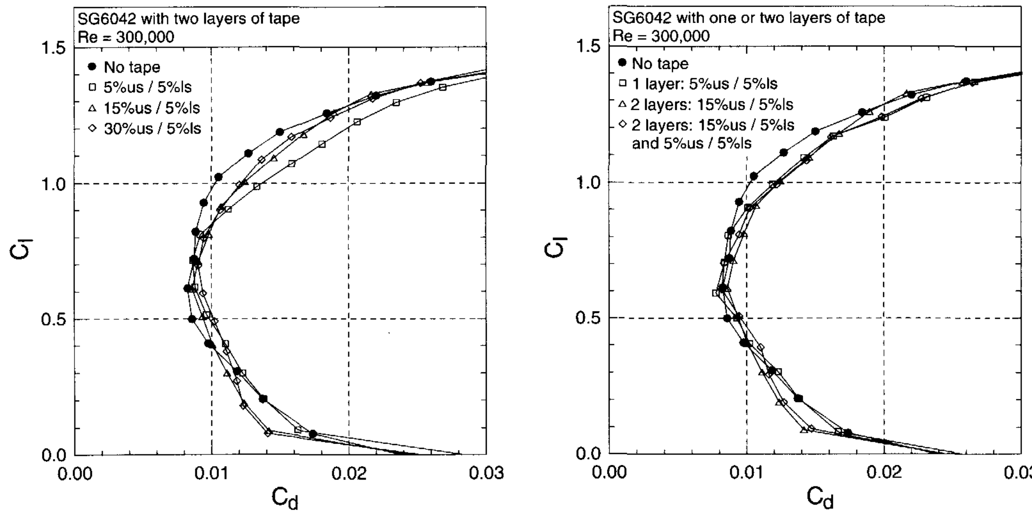

*Figure 7. Drag polars showing the effect of the tape on the SG6042 aerofoil (*Re = *300,000): (a) two layers of tape; (b) one layer and staggered layers of tape*

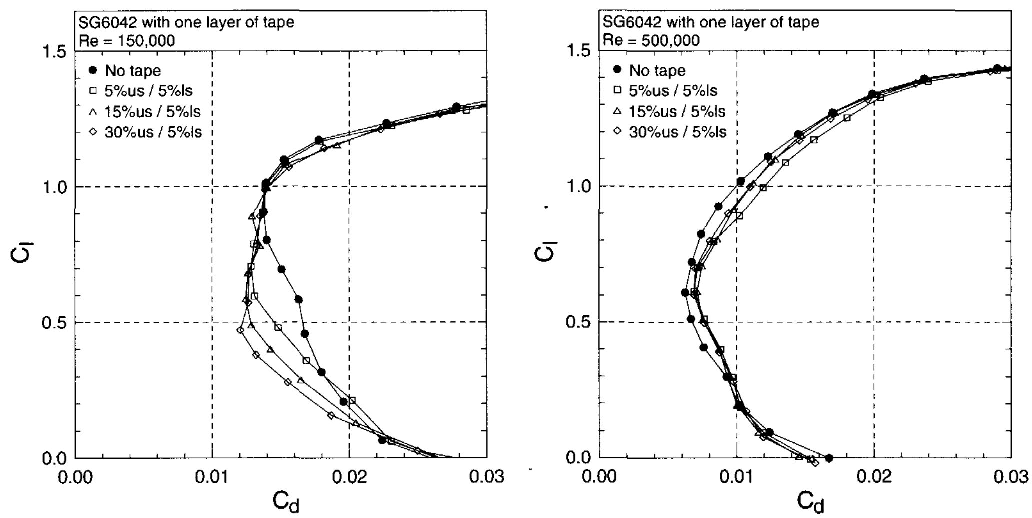

*Figure 8. Drag polars showing the effect of the Reynolds number on the performance of the SG6042 aerofoil (one layer of tape): (a)*Re = *150,000; (b)*Re = *500,000*

and those for two layers ending at 15% chord. These results suggest that it is mainly the first disturbance (backward step) that affects the drag and that extending the second layer beyond 5% chord yields diminishing aerodynamic performance gains versus the amount of tape used. Therefore staggering the tape layers is beneficial as it minimizes the size of the first disturbance, which mainly affects the drag, and the amount of tape used.

The drag polars for the SG6042 aerofoil with one layer of tape at Reynolds numbers of 150,000 and 500,000 are shown in Figure 8. The trends presented in Figures 8(a) and 8(b) can be explained by the behaviour and magnitude of the laminar separation bubble effects, which are dominant at a Reynolds number of 150,000 and small at a Reynolds number of 500,000. Therefore the early transition initiated by the tape provided considerable reduction in overall drag up to a lift coefficient of 0·9 at a Reynolds number of 150,000. At this Reynolds number the tape reduced the maximum lift-to-drag ratio by only

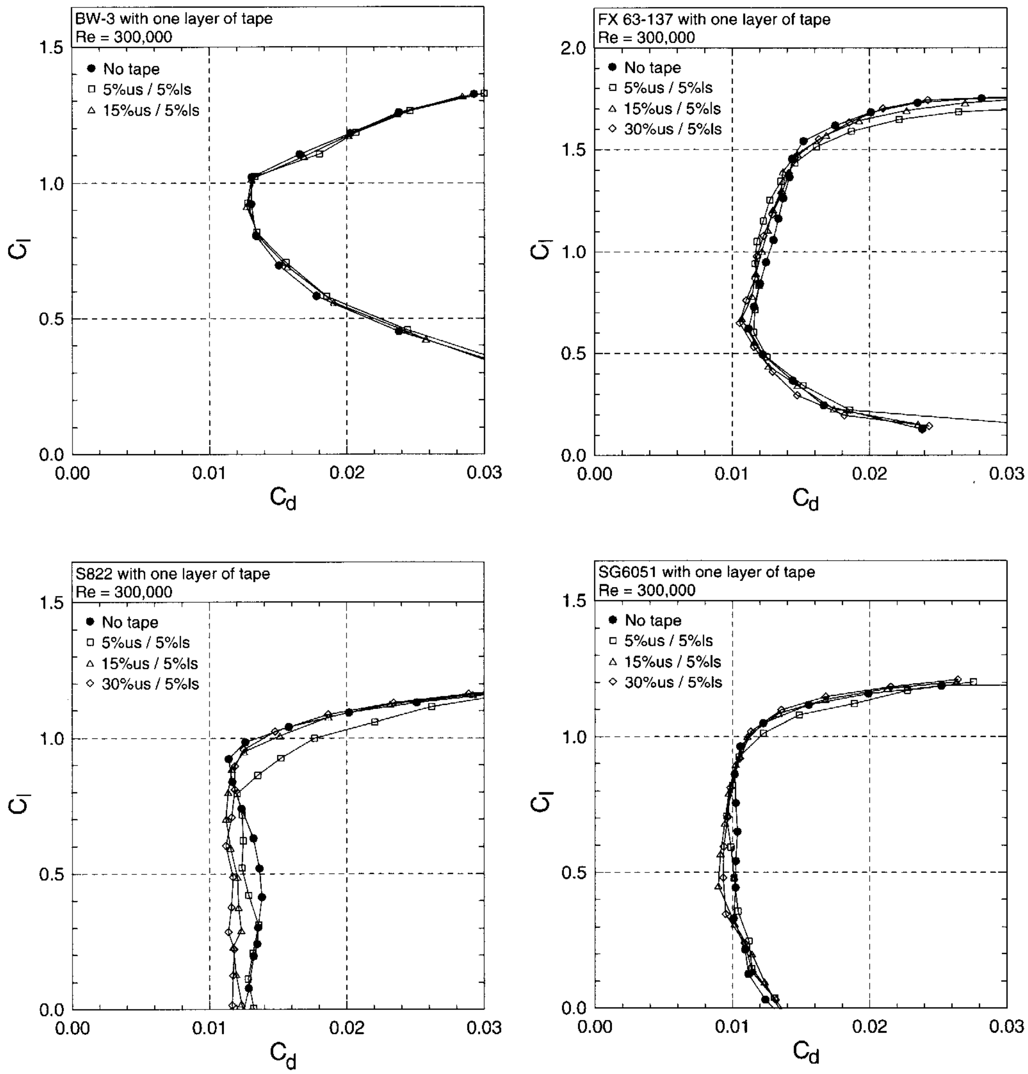

Figure 9. Drag polars showing the effect of varying the tape edge location on the suction surface of various aerofoils (one layer of tape and Re = *300,000): (a) BW-3; (b) FX 63-137; (c) S822; (d) SG6051*

1%–2%. For a Reynolds number of 500,000 the tape mainly resulted in device drag and an increase in skin friction drag. The maximum lift-to-drag ratio was reduced by 10%–15% (Figure 8(b)), which is similar to the results for two layers of tape at a Reynolds number of 300,000 (Figure 7(a)). In effect, a change in Reynolds number is similar to a change in the tape thickness, because they both affect the ratio of the boundary layer thickness to the tape thickness.

The results from the tests conducted with the four other aerofoils considered in this study are presented in Figure 9. These results are for one layer of tape at a Reynolds number of 300,000. For the BW-3 aerofoil, the tape had negligible effect on the drag polar. As flow visualization and XFOIL results both revealed, natural transition for the BW-3 aerofoil occurs in the vicinity of the leading edge.[5] The early transition makes it nearly insensitive to the tape as the results show. For the other three aerofoils the drag reductions shown in Figures 9(b)–9(d) are proportional to the magnitude of the bubble drag on these aerofoils.[5] Laminar separation effects are particularly strong for the S822 aerofoil owing to its high thickness, which caused reductions in maximum lift-to-drag ratio from 5% to 18%. The S822 and

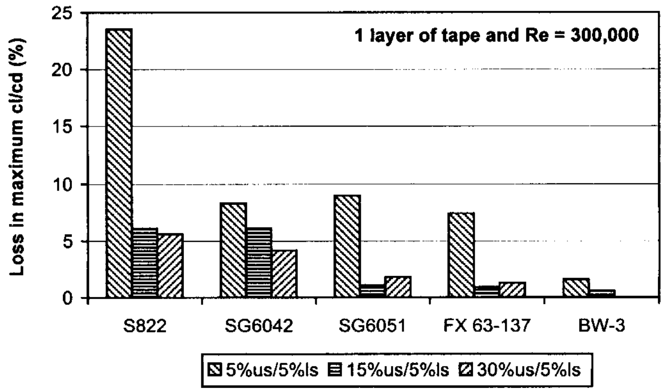

Figure 10. Percentage loss in maximum lift-to-drag ratio from the addition of leading-edge tape corresponding to the angle of attack for best lift-to-drag ratio of the no-tape case (one layer of tape and Re = *300,000)*

SG6051 aerofoils benefit from extending the tape beyond 5% chord, while there is a trade-off between drag in the middle and upper end of the lift range in the case of the FX 63-137 aerofoil. Overall, the tape was less detrimental to the drag as compared with the results obtained with the SG6042 aerofoil, which has lower drag owing to the longer extent of laminar flow over its suction surface. Even though the drag of the SG6042 aerofoil was more sensitive to the tape, it has lower drag with tape than the other aerofoils tested owing partly to its lower thickness. It is important to note that the drag penalties from the tape increase with increasing tape thickness and Reynolds number. Therefore interpolation of the results shown in Figure 9 for a second layer of tape and higher Reynolds numbers should be done with care using the results presented in Figures 7 and 8. In this respect the S822 aerofoil with one layer of tape was also tested at a Reynolds number of 500,000. The results showed no significant drag reductions and larger drag penalties as compared with the results shown in Figure 9(c).[5]

Practical Significance of the Results

The significance of the aerodynamic effects of leading-edge tape on wind turbine performance depends on the size and mode of operation of the turbine. For example, the drag reductions obtained with the tape for Reynolds numbers below 500,000 are favourable to wind turbines having a rated power of approximately 5 kW or less, which typically operate over these low Reynolds numbers. Furthermore, small constant-speed wind turbines are likely to benefit more from these drag reductions as compared with those operating at variable speed owing to their respective operational lift range. Constant-speed wind turbines operate over a broad lift range, while variable-speed turbines are designed to operate over a relatively narrow range of lift coefficients that maximize the lift-to-drag ratio. Consequently, the effect of the tape on the maximum lift-to-drag ratio is more important for variable-speed wind turbines.

Figure 10 presents the loss in maximum lift-to-drag relative to the no-tape case for the different aerofoils tested with one layer of tape at a Reynolds number of 300,000. The losses shown in Figure 10 were evaluated at the angle of attack for best lift-to-drag ratio of the no-tape case, because blades are typically designed with aerofoil data that do not take into account the effects of the tape. Overall, the losses in maximum lift-to-drag ratio are clearly aerofoil-dependent, ranging from 0% to 24%, and ending the tape at 5% chord caused the largest losses incurred by each aerofoil. Further reductions in performance should be expected for variable-speed turbines if the tape also reduces the lift range over which the optimum lift-to-drag ratio occurs owing to change in the operating tip-speed ratio from atmospheric turbulence. The effects of the number of tape layers and the Reynolds number on the loss in maximum lift-to-drag ratio of the SG6042 aerofoil are shown in Figure 11. These losses correspond to the lift coefficient yielding maximum lift-to-drag ratio of the no-tape case. As shown in Figure 11, adding a

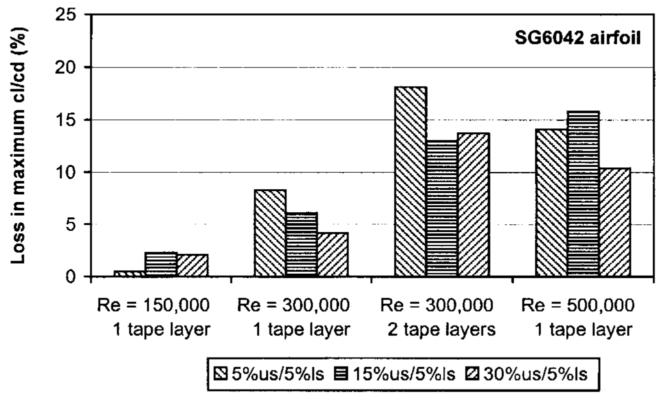

Figure 11. Percentage loss in maximum lift-to-drag ratio from the addition of leading-edge tape corresponding to the angle of attack for best lift-to-drag ratio of the no-tape case (SG6042 aerofoil)

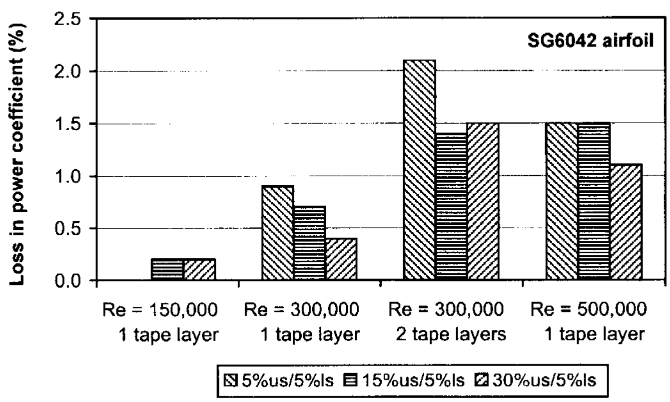

Figure 12. Percentage loss in power coefficient from the addition of leading-edge tape corresponding to the losses in maximum lift-to-drag ratio presented in Figure 11 (SG6042 aerofoil and operating tip-speed ratio of eight)

second layer of tape resulted in a loss in maximum lift-to-drag ratio that is at least twice that for one layer, and these losses were strongly dependent on the Reynolds number.

To quantify the effect of the leading-edge tape on wind turbine performance, the losses shown in Figure 11 were translated into losses in power coefficient for small wind turbines operating at constant tip-speed ratio (variable speed). The computer program PROPID,[14] which is an inverse design method for horizontal axis wind turbines (HAWTs), was used for this purpose. In brief, the approach taken was to optimize the blade geometry (chord and twist) for maximum power coefficient (axial inflow coefficient of 1/3 and lift coefficient for maximum lift-to-drag ratio along the entire blade) using the aerofoil data for the no-tape case. The aerofoil data were fixed for a given Reynolds number, and a blade was designed for Reynolds numbers of 150,000, 300,000 and 500,000. A 5 kW wind turbine having a three-bladed rotor of 5 m (16·4 ft) in diameter and operating at a constant tip-speed ratio of eight was used for the three blade designs. The optimized rotors were then analysed using the aerofoil data with leading-edge tape, again by fixing the aerofoil data for a particular Reynolds number and tape configuration. Because each analysis was performed at constant tip-speed ratio for a given Reynolds number, the rotors were operating at constant power coefficient (ideal case). Figure 12 presents the losses in power coefficient for the same cases shown in Figure 11. These losses are small and are approximately 10% of the corresponding losses in lift-to-drag ratio. Such smaller losses in power coefficient compared with those in lift-to-drag ratio can be traced to the relatively small effect of the tape in lift, which does not particularly affect torque. Although the losses in power coefficient shown in Figure 12 are small, they rapidly increase with the number of tape layers and Reynolds number. From the trends shown in Figure 12, a 4%–5% loss in power coefficient can be expected for two layers of tape at a Reynolds number of 500,000. Therefore special attention should be given to the application of the tape for turbines operating at a Reynolds number of 500,000 or larger (approximately 5 kW or larger), particularly if two layers of tape are used. Additional losses in wind turbine performance should be expected from off-design operations caused by atmospheric turbulence if the tape reduces the lift or angle of attack range for which near-maximum lift-to-drag ratio is achieved.

Conclusions

Prior to this study the aerodynamic effects of leading-edge tape had not been systematically investigated. The wind tunnel tests conducted have shed some light on these effects on low-Reynolds-number aerofoils. As expected, the tape was shown to trigger early transition to turbulent flow, and the resulting effect on drag depended on the trade-off between bubble, device and skin friction drag. Therefore the magnitude of the aerodynamic effects caused by the tape is aerofoil-dependent. The wind tunnel results were used to quantify the corresponding effects on the wind turbine performance. For variable-speed HAWTs operating at constant tip-speed ratio, and thus at constant power coefficient, the different tape configurations tested on the SG6042 aerofoil reduced the power coefficient by approximately 2% or less. Despite the small losses in power coefficient, these losses were found to increase rapidly with the number of tape layers and Reynolds number. Therefore the loss in power coefficient can be expected to increase for wind turbines operating at Reynolds numbers above 500,000. As a practical consequence, special attention should be given to the application of the tape for wind turbines with ratings of the order of 5 kW, particularly if two layers of tape are used. To minimize the loss in performance from the use of leading-edge tape, the following application guidelines are suggested.

- The chordwise extent of the tape on the pressure surface can be selected according to the expected impingement limits, because it was found to have negligible effect on aerofoil performance.
- Unless turbulent flow aerofoils are used, the location of the tape edge on the suction surface has a much larger effect on aerofoil performance compared with that on the pressure surface. Ending the tape relatively close to the leading edge, such as 5% chord, should be avoided as it typically reduces aerofoil performance. Aerodynamically, a better option is to extend the tape to 15%–30% chord. Therefore protecting a larger portion of the suction surface with tape results in a smaller reduction in aerofoil performance.
- When multiple layers of tape are used, which is typical for the outboard section of the blades, it is preferable to stagger the layers over ending them at the same location.

The loss in performance caused by the tape can of course be minimized by designing the blades using aerofoil data that account for the effects of the tape, and using thinner tape. Unfortunately, such aerofoil data are limited, and using thinner tape may defeat its purpose. Therefore relying on the application guidelines given above is likely to be the best strategy to minimize the loss in performance when using leading-edge tape.

Acknowledgements

The support of the National Renewable Energy Laboratory under subcontract XAF-4-14076-03 is gratefully acknowledged. The authors also want to thank James L. Tangler for his suggestions and for reviewing the paper. In addition, discussions with Clint (Ito) Coleman of The New World Power Technology Company were useful in the preparation of this work. The authors wish to thank Mark Allen

(BW-3, FX 63-137, S822 and SG6042) and Mike Fox (SG6051) for building the wind tunnel models of the aerofoils tested in this study. Also, Melanie Bevis of World Power Technologies is thanked for providing information about the tape used on their wind turbines. Finally, the reviewers are thanked for their helpful comments and suggestions.

References

1. C. Coleman and D. J. Mayer 'North Wind 4 kilowatt wind system development: Phase I—Design and analysis, Phase II—Technical report', *Subcontractor Report Submitted to Rocky Flats Wind Energy Research Center, Subcontract PF08501C*, 1982.
2. T. L. Forsyth, 'An introduction to the small wind turbine project', *AWEA Wind Power '97 Conf.*, Austin, TX, 1997.
3. M. F. Kerho and M. B. Bragg, 'Airfoil boundary-layer development and transition with large leading-edge roughness', *AIAA J.*, **35**, 75–84 (1997).
4. C. A. Lyon, M. S. Selig and A. P. Broeren, 'Boundary-layer trips on airfoils at low Reynolds numbers', *AIAA Paper 97-0511*, 1997.
5. P. Giguère and M. S. Selig, 'A wind tunnel investigation of the aerodynamic effects of leading-edge tape on airfoils at low Reynolds numbers', *Report AAE 98-05, UILU ENG 95-0505*, Department of Aeronautical and Astronautical Engineering, University of Illinois at Urbana–Champaign, 1998.
6. P. Giguère and M. S. Selig, 'Low Reynolds number airfoils for small horizontal axis wind turbines', *Wind Engng.*, **21**, 367–380 (1997).
7. M. S. Selig, J. J. Guglielmo, A. P. Broeren and P. Giguère, *Summary of Low-speed Airfoil Data—Volume 1*, SoarTech Publications, Virginia Beach, VA, 1995.
8. C. A. Lyon, A. P. Broeren, P. Giguère, A. Gopalarathnam and M. S. Selig, *Summary of Low-speed Airfoil Data—Volume 3*, SoarTech Publications, Virginia Beach, VA, 1997.
9. J. J. Guglielmo and M. S. Selig, 'Spanwise variations in profile drag for airfoils at low Reynolds numbers', *J. Aircraft*, **33**, 699–707 (1996).
10. P. Giguère and M. S. Selig, 'Velocity correction for two dimensional tests with splitter plates', *AIAA J.*, **35**, 1195–1200 (1997).
11. P. Giguère and M. S. Selig, 'New airfoils for small horizontal axis wind turbines', *ASME J. Solar Energ. Engng.*, **120**, 108–114 (1998).
12. P. Giguère and M. S. Selig, 'Design and wind tunnel test result for the SG6050 and SG6051 airfoils', *Report AAE 98-04, UILU ENG 95-0504*, Department of Aeronautical and Astronautical Engineering, University of Illinois at Urbana–Champaign, 1998.
13. M. Drela, 'XFOIL: an analysis and design system for low Reynolds number airfoils', in T. J. Mueller (ed.), *Low Reynolds Number Aerodynamics*, Vol. 54 of Lecture Notes in Engineering, Springer-Verlag, New York, 1989, pp. 1–12.
14. M. S. Selig and J. L. Tangler, 'Development and application of a multipoint inverse design method for horizontal axis wind turbines', *Wind Engng.*, **19**, 91–105 (1995).

