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Wind Turbine Trailing Edge Aerodynamic Brakes

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ABSTRACT

Five trailing-edge devices were investigated to determine their potential as wind-turbine aerodynamic brakes, and for power modulation and load alleviation. Several promising configurations were identified. A new device, called the spoiler-flap, appears to be the best alternative. It is a simple device that is effective at all angles of attack. It is not structurally intrusive, and it has the potential for small actuating loads. It is shown that simultaneous achievement of a low lift/drag ratio and high drag is the determinant of device effectiveness, and that these attributes must persist up to an angle of attack of 45°. It is also argued that aerodynamic brakes must be designed for a wind speed of at least 45 m/s (100 mph).

INTRODUCTION

Most wind turbines incorporate an overspeed-protection system that relies upon the reduction of aerodynamic forces to reduce torque and power. These systems are sometimes complex, heavy and costly. As researchers develop better analytical tools and become more sophisticated in their design philosophies, attempts are being made to develop innovative aerodynamic devices to solve these problems. In some cases, the same devices used for overspeed protection may also be used to modulate power and alleviate structural loads. Several turbine designers are currently developing advanced aerodynamic devices for use on their own wind turbines. NREL is providing assistance to these designers while simultaneously pursuing a comprehensive research initiative with promising long-term benefits for the entire wind industry. Recently, this research has focused on the development of an aerodynamic brake that provides an alternative to existing approaches. Some of the design goals for the device are reliability, maintainability, light weight, fail-safe design, low cost, suitability for active control, and the potential for passive actuation.

A review of aerodynamic design considerations and a survey of various control devices is contained in Reference 1, where it is noted that overspeed protection is one of the most important and challenging aspects of wind turbine design. When a rotor experiences a loss of load, it will accelerate rapidly until it reaches a state of zero torque at some equilibrium rotational speed. Without corrective action, this process will almost certainly result in structural damage. Because overspeed protection is so critical, it is common design practice for wind turbines to incorporate two independent braking systems, one of which operates directly on the torque-producing aerodynamic forces. On some turbines, the aerodynamic brakes are routinely used for shutdown, in order to reduce the loads on the gearbox and mechanical brake.

Full-span or partial-span pitch control has been employed on many turbines. Although this approach is quite effective, it is costly, and unlikely to be used unless other design considerations favor variable pitch. Rotating blade tips and tip vanes are also very effective, because they act in the region where a relatively large percentage of the rotor torque is generated. Rotating tips have been used on wind turbines for many years, but they are heavy, costly, structurally intrusive, and unsuitable for active control. Tip vanes have been used effectively on several turbines, but they too are unsuitable for active control. And because their size increases in proportion to rotor swept area, they may be inappropriate for large turbines. Furthermore, they do not alleviate blade loads; they simply impose an additional drag load at the blade tip to produce counter-torque. Because each of these approaches–variable pitch, rotating tips and tip vanes–is accompanied by undesirable characteristics, there is ample reason to consider new alternatives. In this study, trailing-edge devices were selected for consideration. Table 1 identifies several of the design objectives for these devices, along with some clarifying comments.

TABLE 1. DESIGN OBJECTIVES FOR TRAILING EDGE DEVICES

Design Objective	Comment
Aerodynamic braking	Requires negative torque to $\alpha \approx 40°$ or greater
Power modulation	Requires monotonic response
Small size	Minimizes weight and cost
Minimum intrusion into rotor structure	Maintains structural integrity
Low hinge moments	Minimizes actuator size, weight, cost
Moderate thickness	Maintains stiffness; minimizes bending
Low mass; center of gravity at hinge line	Avoids flutter

After a period of dormancy following their application by NASA, trailing-edge devices are now being considered by New World Power Company, PS Enterprises, R. Lynette & Associates, and Zond Systems. There are several reasons why these devices are of interest. They make good use of the existing blade structure, and should add very little weight. Their deployment causes a substantial lift decrement, which alleviates fundamental blade loads during braking events. Their own aerodynamic and inertial loads are easily transferred to the primary blade structure with minimum intrusion into the spar or torque box. This should result in superior strength and stiffness. And because their loads are distributed along the blade span, structural dynamics should be minimally impacted. Finally, a considerable effort has already been devoted to the use of these devices, and there is a large body of relevant literature to assist designers.

AERODYNAMIC DESIGN CONSIDERATIONS

In considering the aerodynamics of trailing-edge devices, it is helpful to begin with fundamental principles. When used as aerodynamic brakes, their purpose is to diminish the forces which produce blade torque. At a given spanwise location, the torque coefficient is given by:

$$C_q = C_l \sin(\phi - \beta) - C_d \cos(\phi - \beta) \qquad \text{Equation (1)}$$

where C_l and C_d are the section lift and drag coefficients, ϕ is the angle between the relative inflow velocity and the blade plane-of-rotation, and β is the sum of the blade pitch and twist angles (β is positive with the blade leading edge rotated into the wind toward feather). For an untwisted blade section at zero pitch angle, $(\phi - \beta) = \alpha$, the section angle of attack. In considering the attributes of a particular device, it is customary to consider the chordwise force coefficient, which is given by:

$$C_s = C_l \sin(\alpha) - C_d \cos(\alpha) \qquad \text{Equation (2)}$$

This quantity is referred to throughout the literature as the "leading-edge suction coefficient," and it is widely used to evaluate various aerodynamic brake configurations. A negative suction coefficient implies a negative contribution to torque, which is the obvious design goal for aerodynamic brakes. At angles-of-attack prior to stall, the lift coefficient is commonly two orders of magnitude larger than the drag coefficient, with $C_l / C_d \approx 60$ being typical. In this situation, $\sin(\alpha)$ is much less than $\cos(\alpha)$, but the lift term still dominates Equation 2. As shown in Reference 1 for several commonly used airfoils, peak suction coefficients of $C_s \approx 0.3$ typically occur for wind-turbine blades in normal operating conditions.

An important observation must be made regarding the relative impact of C_l and C_d in aerodynamic braking applications. Examination of Equation 2 shows that even large C_l decrements are of little consequence at low α, because $\sin(\alpha)$ is very small. On the other hand, large C_d increments are very desirable at low α, because $\cos(\alpha)$ is very large. Figure 1 illustrates this point by showing the relative importance of C_d compared to C_l, which is plotted simply as $\cos(\alpha) \div \sin(\alpha)$. Note that at $\alpha = 10°$, the relative impact of C_d on C_s is more than five times greater than the impact of C_l on C_s. Even at $\alpha = 25°$, C_d has twice the impact of C_l. Other important observations can be made by expressing the suction coefficient in the following form.

$$C_s = C_d \left[(C_l/C_d) \sin(\alpha) - \cos(\alpha) \right] \qquad \text{Equation (3)}$$

This equation makes it clear that a necessary attribute of an aerodynamic brake is the reduction of C_l / C_d to a value that causes the suction coefficient to become negative. It is also important for the reduction of C_l / C_d to be accompanied by a large drag increase. Indeed, as illustrated by Miller [2], the most effective aerodynamic brake configurations demonstrate $C_l / C_d \approx 0.3$ with $C_d \approx 1.0$.

The objective is to maximize the decrement in suction coefficient resulting from deployment of the aerodynamic brake, and to assure that the suction coefficient remains negative throughout the anticipated angle of attack range. The more negative the suction coefficient is, the smaller the device must be to achieve the desired braking capability. The angle of attack is determined (vectorially) by the design wind speed (V_w) and blade rotational speed (RPM). Unfortunately, neither the literature nor common design practice provide much guidance regarding the choice of V_w and RPM. A typical design scenario involves an abrupt loss of load; a situation which may occur in high winds. But how high? Selection of $V_w = 30$ m/s (67 mph), which is the approximate cut-out speed for many turbines, is not prudent because it does not allow for gusts. If the design penalties are not too severe, $V_w = 60$ m/s (134 mph) is a good choice, because that is the survival wind speed selected for many turbines. A strong case may be made that the design wind speed should be at least $V_w = 45$ m/s (100 mph), which represents a typical cut-out speed plus an extreme coherent gust of 15 m/s (33 mph).

Figure 2 was constructed to provide guidance in selecting the angle of attack range for which device effectiveness must be maintained. It shows the local angle of attack as a function of blade station for several current-generation turbines operating at synchronous speed. Using $V_w = 45$ m/s (100 mph) for illustration purposes, and assuming that the trailing-edge device may be located as far inboard as 65% span, Figure 2 illustrates that the device should operate effectively up to an angle of attack of approximately 45°. Otherwise, its performance will be inadequate at high wind speeds.

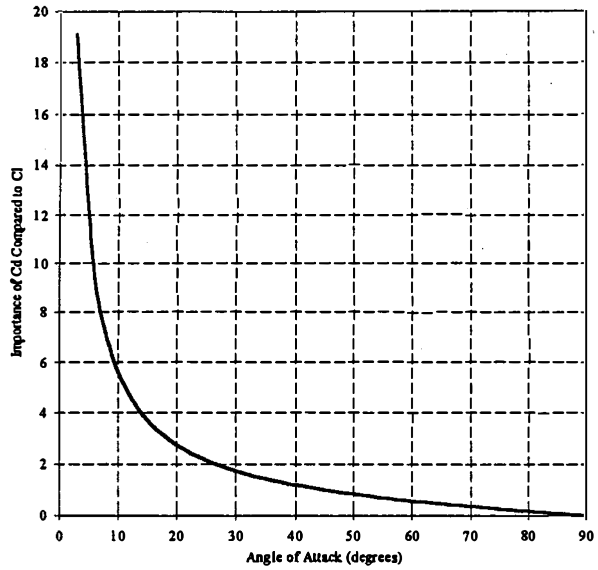


FIGURE 1. IMPACT OF C_d AND C_l ON C_s

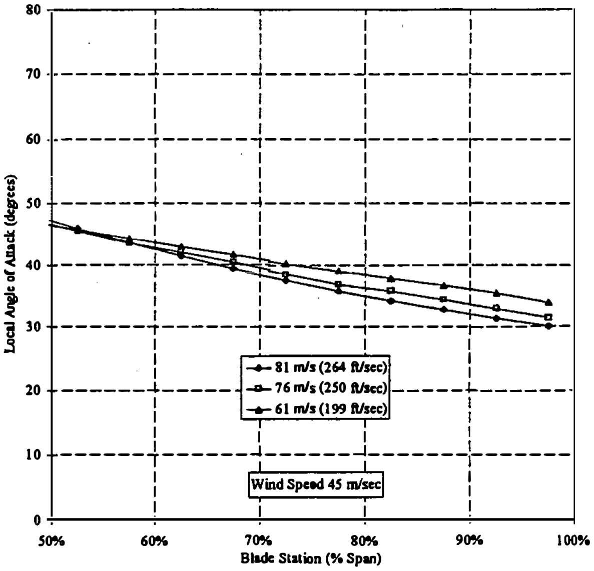


FIGURE 2. BLADE STATION ANGLE OF ATTACK

It may be concluded from the foregoing discussion that devices producing a large drag increment are good candidates for aerodynamic brakes, as long as they do not simultaneously produce a large lift increment. This combination of attributes is inconsistent with most aerodynamic controls, such as spoilers, flaps and ailerons. Nevertheless, the possibility of achieving this result was demonstrated by Rogallo [3] in National Advisory Committee for Aeronautics (NACA) studies of aircraft dive brakes, where it was shown that the lift increment produced by a 25%-chord slotted flap could be offset by the lift decrement produced by a 10%-chord spoiler. He also observed that allowing a gap ("venting") between the deflected trailing-edge device and the main airfoil increased effectiveness at low angles of attack. Other NACA studies by Toll and Ivey [4] showed promising results for the application of double split-flaps to wind-turbine blades. Guided by these observations, several new configurations were suggested by Quandt [5] and subsequently evaluated in exploratory wind-tunnel tests [2, 6] at Wichita State University (WSU). The tests were conducted on a 0.46-m- (1.5-ft-) chord model of an NACA 64_3-618 airfoil at Reynolds Numbers (Re) of approximately one-million. Re was determined by model construction, not tunnel limits.

WIND TUNNEL TESTS

As a result of consultations with other researchers, and guided by the literature, five configurations were selected for wind-tunnel testing. The first is a "***double split-flap***" inspired by Reference 4 and consisting of upper and lower surfaces of approximately 30% chord deflected simultaneously to 60°. A similar device is used on U. S. Air Force B-52 and U. S. Navy A-6 aircraft to shorten landing distances. The second device resembles a "***clamshell***" and was addressed as such throughout the study. It consists of upper and lower surfaces of approximately 20% chord deflected simultaneously to 112°. A similar device was investigated by Penna [7] for use on vertical-axis wind turbines. For both of these devices, several chord-sizes and gaps were investigated in an attempt to identify the optimums. The third device resembles a plain flap, except that it is hinged on the forebody (ahead of the deflected device) and above the chord line. Its concave leading edge rides over a smooth "***round shoulder***" without venting. When the device is deployed, the exposed trailing edge of the forebody has a large curvature, which promotes attached flow and large suction forces as a result of the Coanda effect. The fourth device, the "***spoiler-flap***" attributed to Quandt [5], combines the characteristics of both spoilers and flaps. It achieves the same effect as observed by Rogallo [3], but in a single-element device. When deployed, the device produces a large drag increment, and the lift increment produced by the downward flap deflection is offset by the lift decrement produced by the protruding upper-surface spoiler. The fifth device resembles a plain flap with negative deflection, except that it is not necessarily hinged on the chord line. When deflected, it produces "***negative camber***" which results in a lift decrement in combination with a large drag increment. Many variations of this device, sometimes referred to as the "vented aileron," have been investigated by researchers at WSU and elsewhere. For that reason, it was used as a benchmark in this study.

Figure 3 is a plot of the suction coefficients for these five devices as a function of angle of attack. The geometries represented are those which exhibited the greatest braking effectiveness. The ***round-shoulder*** device is highly effective in the angle of attack range from 10° to 30°, but beyond that its performance deteriorates dramatically. As noted in the previous discussion and illustrated in Figure 2, to be effective at wind speeds of 45 m/s (100 mph) a device must maintain a highly negative suction coefficient up to an angle of attack of approximately 45°. Therefore, the round shoulder device is not a suitable candidate. The ***negative-camber*** device exhibits the desired behavior, but it is less effective than the remaining devices. Therefore, it was eliminated from further consideration. The double split-flap is a highly effective device, particularly at angles-of-attack less than 20° and greater than 50°. However, these are not the regions of importance for the design of an aerodynamic brake (unless it is desired to stop the rotor completely, in which case the high angles of attack are important). For this reason, the double split-flap is no more desirable than the remaining two devices. The ***spoiler-flap*** and ***clamshell*** devices are approximately equal in effectiveness up to 45° angle of attack, beyond which the clamshell device loses effectiveness rapidly.

Because it exhibited the best overall aerodynamic effectiveness, the spoiler-flap was identified as the most promising configuration for continued study. It should also be easier to implement both mechanically and structurally, and it has the potential for small actuating loads.

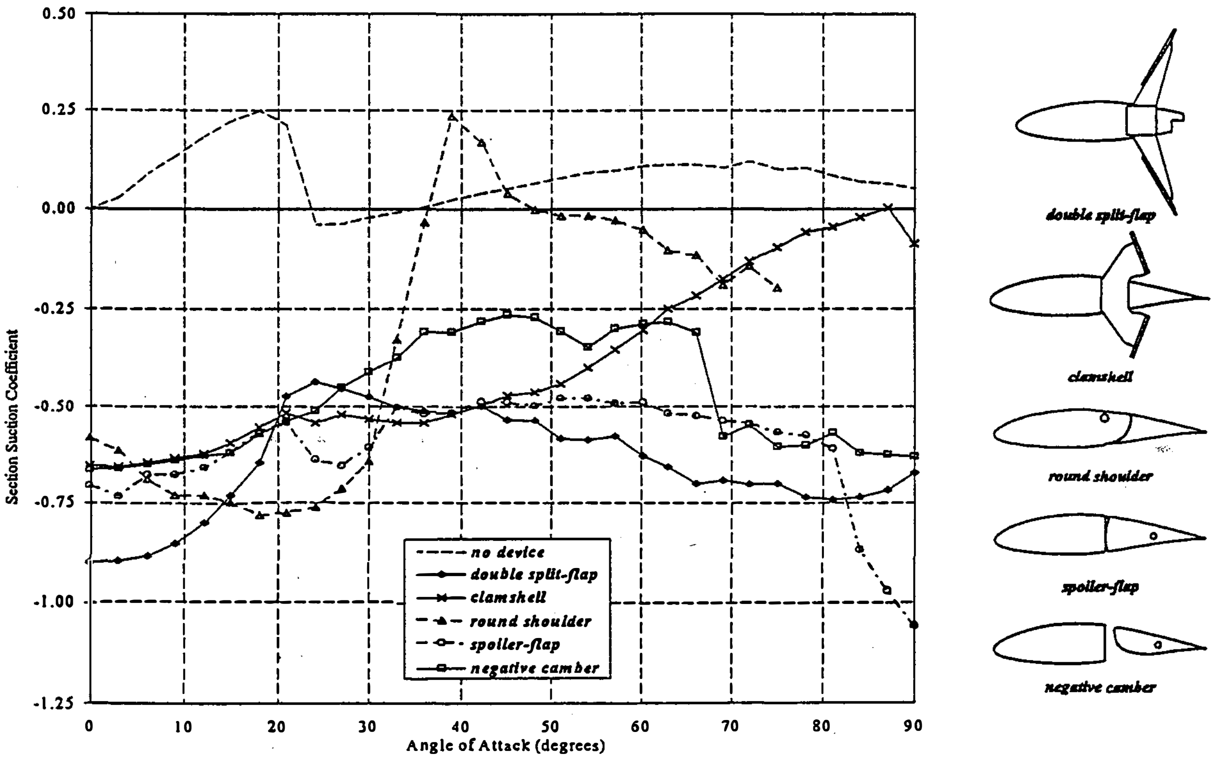
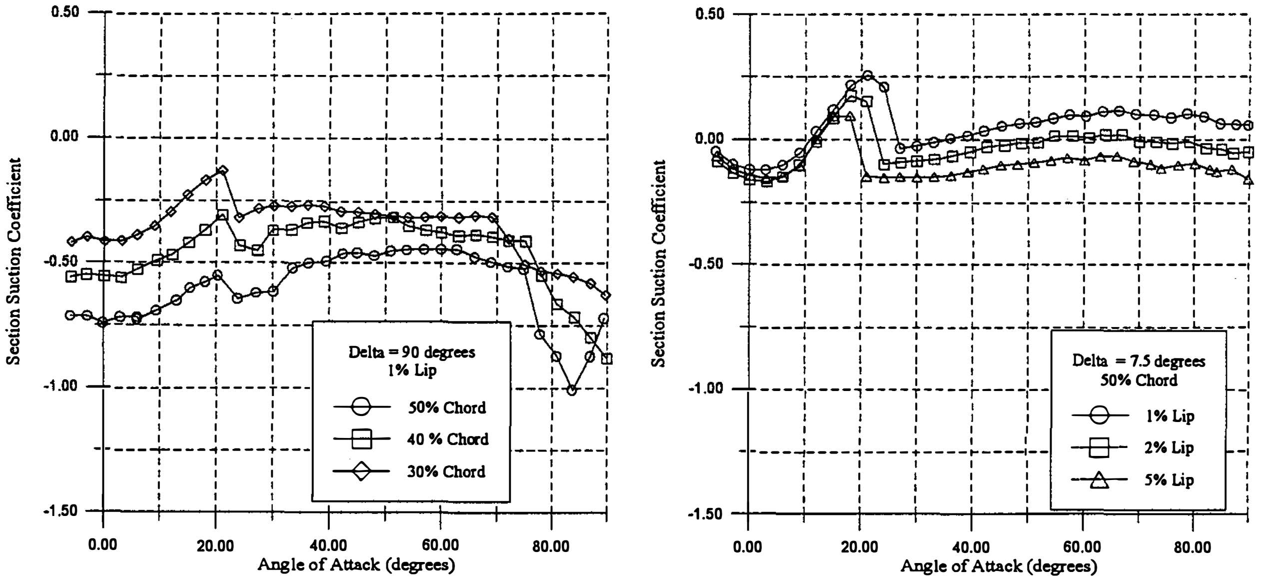
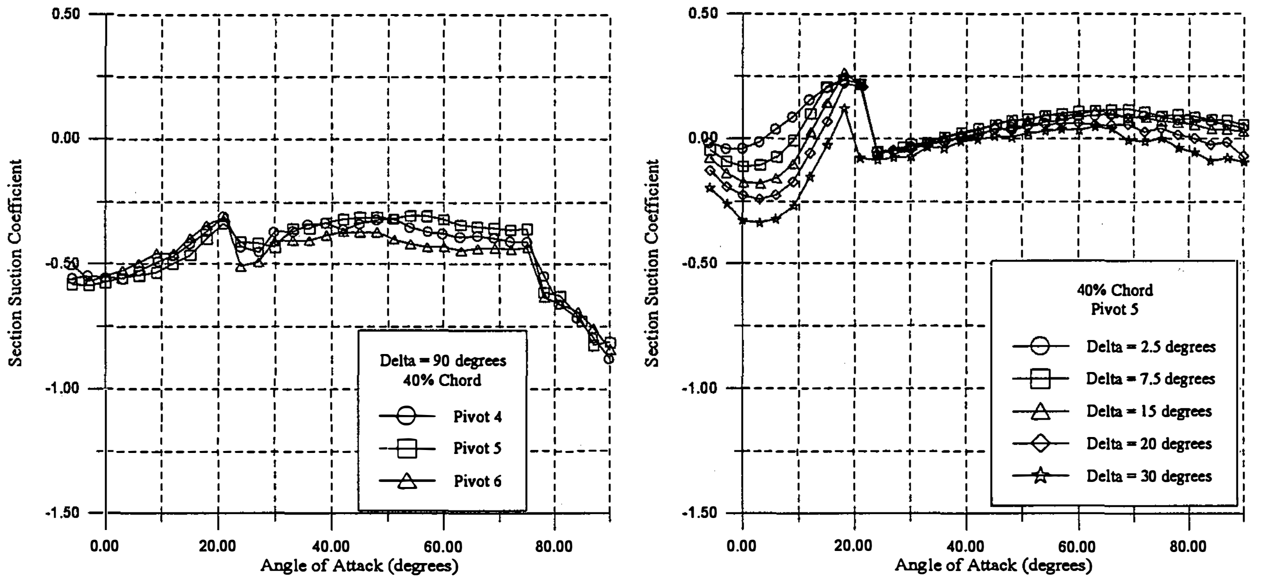


FIGURE 3. EFFECTIVENESS OF TRAILING-EDGE AERODYNAMIC BRAKES

Follow-on wind-tunnel tests conducted at WSU investigated the influence of device chord, hinge position, venting, and lip size on spoiler-flap effectiveness, as well as its suitability for active control. Figure 4 shows the effect of device chord on suction coefficient for a deflection of $\delta = 90°$, which is typical of the aerodynamic brake. Figure 5 shows the significant impact of the upper-surface, leading-edge protrusion (the "lip") on the suction coefficient for $\delta = 7.5°$. It was hypothesized that the lip would have this effect, but it was also incorporated as a mechanism for aerodynamic sealing. The noticeable impact of the lip persists up to deflection angles of $\delta = 30°$, but does not appear at $\delta = 90°$. Figure 6 shows an important attribute of the spoiler-flap; it maintains effectiveness for a wide range of pivot locations. This permits the achievement of a desired hinge moment without destroying the inherent effectiveness of the device. Figure 7 shows that the spoiler-flap is well-behaved at low deflections. Because it can also be configured to have low hinge moments, it appears to be suitable for turbines requiring active control devices.



FIGURES 4 & 5. EFFECT OF CHORD AND LIP SIZE ON EFFECTIVENESS



FIGURES 6 & 7. EFFECT OF PIVOT LOCATION AND DEVICE DEFLECTION ON EFFECTIVENESS

SIZING CRITERIA FOR AERODYNAMIC BRAKES

In the analysis of wind-tunnel data, device effectiveness was evaluated in terms of suction coefficient. It is also instructive to examine the torque produced by rotor blades with the devices installed. For this purpose, hypothetical blades were modeled and their performance calculated [5] in terms of torque versus wind speed. The incremental lift and drag produced by the devices were used to synthesize a set of aerodynamic force coefficients for use in calculating rotor performance. Three current-generation, utility-scale turbines were evaluated. Results indicated that spoiler-flaps of 40%-50% chord, applied to the outboard 15%-20% of the blade, provided effective overspeed protection for stall-regulated rotors designed with airfoils having low maximum lift coefficients in the blade-tip region. Rotors that were not designed for stall regulation, or those that were designed using conventional airfoils in the blade-tip region, required device spans of 30% or greater to achieve effective overspeed control. It was also shown that the size of the spoiler-flap is significantly influenced by the design criteria chosen for overspeed protection.

The point was made earlier that the design wind speed should be at least 45 m/s (100 mph). The question remains, however, as to what the maximum permissible rotational speed (RPM) should be. Some certification agencies require that the turbine be capable of withstanding rotational speeds ***at least*** 25% higher than synchronous speed, but it is not clear what wind speed coincides with this requirement. All of the devices investigated will perform better at higher rotational speeds, because their retarding torque is proportional to dynamic pressure (and the square of rotational speed). Smaller devices, presumably having lower cost, will result from the choice of higher design RPM. Logically, if the turbine is already designed to withstand rotational speeds 25% higher than synchronous, this should also be the design RPM for the aerodynamic brake. But other factors must be considered. For example, the ultimate strength of the blades and tower may be dictated by the loads imposed with the rotor parked (RPM = 0) at survival wind speed. These loads may be exceeded at wind speeds of 45 m/s (100 mph) and RPM = 1.25 x synchronous. The appropriate resolution of this dilemma is to consider the design of aerodynamic brakes along with other design load cases. When the implications are known, an intelligent choice can be made. These considerations are beyond the scope of this paper, and are left for the designer to ponder. Fortunately, using the spoiler-flap or another device of similar effectiveness, the allowable rotational speed can be controlled as desired by simply increasing the chord or span of the device.

Figure 8 illustrates the effect of device size on rotor torque. It was constructed for a hypothetical, stall-regulated turbine of 25-m diameter operating at a synchronous tip speed of 76 m/s (250 ft/sec). A 50%-chord spoiler-flap with its outboard station at 95% of blade span was simulated. A 10%-span device is inadequate, because it allows positive torque at wind speeds between 15 m/s and 25 m/s. A 15%-span device is more than adequate. Extrapolation between the two curves indicates that a 12%-span device would produce negative torque at all wind speeds below 52 m/s. Examination of Figure 9, which was constructed for a tip speed of 1.25 x synchronous, indicates that a 12%-span device would prevent positive torque at all wind speeds below 60 m/s. Figure 10 shows the capability of a 20%-span, 40%-chord spoiler-flap to limit the rotor to synchronous speed at wind speeds up to 58 m/s, and it illustrates that the span of the device can be reduced to 15% if the tip speed constraint is relaxed to 1.25 x synchronous.

It is important to note that these calculations were made for illustration purposes only. Many assumptions were made in the interpretation of the wind-tunnel data for use in these calculations. The two-dimensional aerodynamic force coefficients were not corrected for full-scale Reynolds Number or the effects of finite span, unsteadiness, and spanwise flow. Preliminary attempts made to assess the impact of these corrections indicate that the span of the devices calculated from wind-tunnel data would have to increase by approximately 20% to achieve the calculated results. Thus, a device estimated to be 15% of blade span might actually have to be 18%.

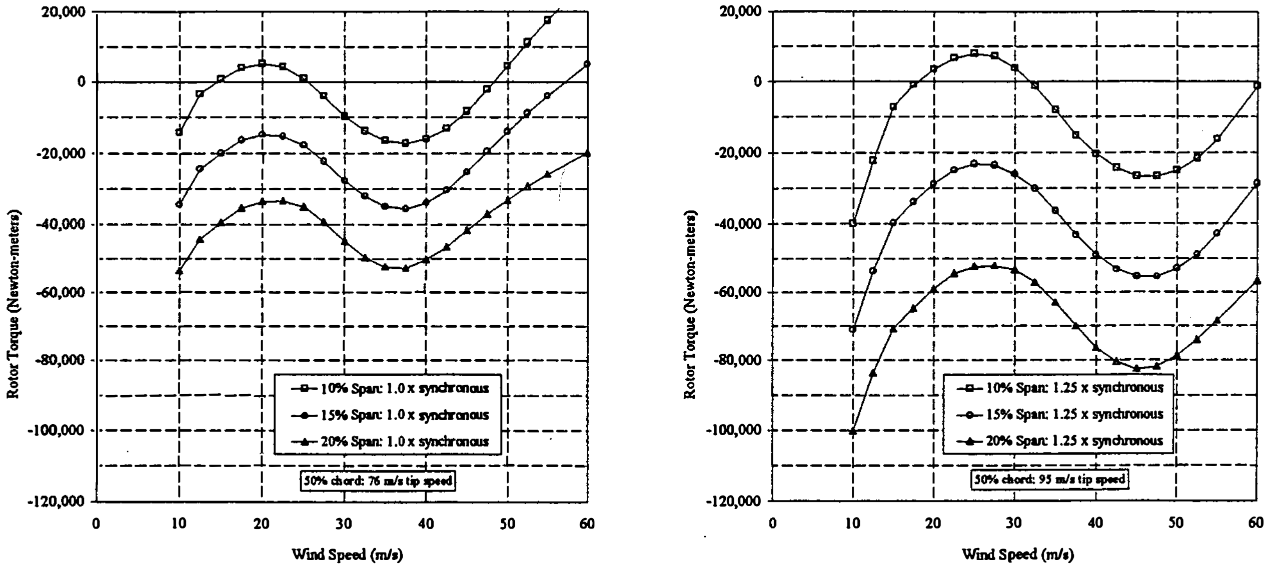


FIGURE 8 & 9. EFFECT OF SPAN AND DESIGN RPM ON AERODYNAMIC BRAKE SIZE

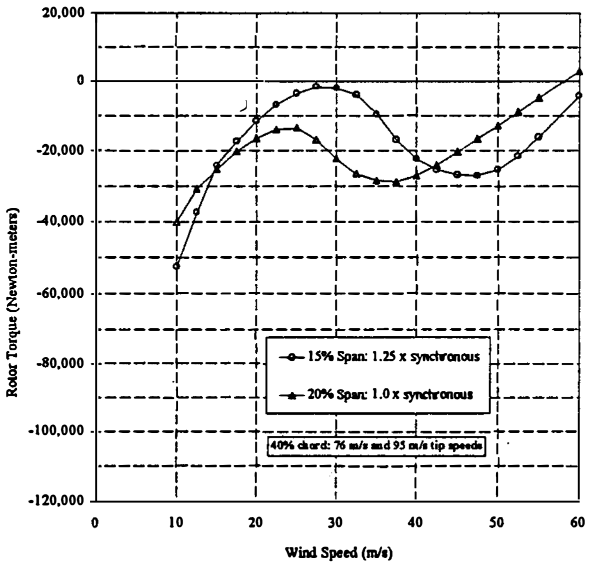


FIGURE 10. EFFECT OF SPAN AND DESIGN RPM ON AERODYNAMIC BRAKE SIZE

The equilibrium tip-speed ratio (TSR) of a rotor is sometimes used as a measure of the effectiveness of its aerodynamic brake. For example, an equilibrium TSR = 2.0 might be considered a good target. But this reference is of little value unless the design tip speed is known, and unless the turbine can tolerate the equilibrium tip-speed ratio at the maximum wind speed for which the aerodynamic brake is designed. Consider an unrestrained rotor with an equilibrium TSR = 2.0 freewheeling in a 45 m/s wind. The tip speed is 90 m/s (2.0 x 45 m/s). This condition might be acceptable for a low-solidity, high-RPM turbine having a design tip speed of 80 m/s. But it could be a problem for a high-solidity, low-RPM turbine having a design tip speed of 60 m/s, for which this condition represents a 50% overspeed. Conversely, a rotor with a design tip speed of 60 m/s at a 45 m/s wind speed would need to demonstrate an equilibrium TSR = 1.33 (60 m/s ÷ 45 m/s). Thus, it is probably best to describe an aerodynamic brake in terms of the maximum RPM - V_w at which it is expected to operate, rather than an equilibrium TSR.

CONCLUSIONS

A considerable effort has been made by contemporary researchers to better understand the aerodynamics of trailing-edge devices. The objective of their work is to qualify these devices as alternatives to traditional overspeed-protection methods--variable pitch, rotating tips and tip vanes. In connection with the present study, conclusions that may be drawn from the wind-tunnel tests, and the subsequent analysis, are as follows.

- The most important aerodynamic attribute of a trailing-edge device is the simultaneous production of a large drag increment and a significant reduction in the lift-to-drag ratio.

- The effectiveness of the device must be maintained throughout the angle of attack range in which it operates, which is determined by spanwise location on the blade, RPM, and wind speed. Examination of several representative turbines suggests that this angle of attack should be 40° to 45°. If aerodynamic effectiveness diminishes below this angle of attack, larger devices will be required, or overspeed protection will deteriorate at high wind speeds, or both.

- The aerodynamic performance of the ***spoiler-flap***, ***double split-flap,*** and ***clam shell*** device is comparable, and all are superior to the ***round-shoulder*** and ***negative-camber*** devices.

- The spoiler-flap seems to be the best overall design choice. Its aerodynamic performance is good at all angles of attack; it is a simple device; it should be structurally less intrusive; as shown in follow-on wind-tunnel tests, it has moderate and controllable hinge moments; its monotonic variation of suction coefficient with deflection angle make it suitable for active control applications.

- The choice of design RPM and wind speed, which are critical in sizing the aerodynamic brake, are not intuitively obvious. It would be helpful if international standards groups and certification agencies could provide guidance in this regard.

- The effects of full-scale Reynolds Number, finite span, unsteadiness, and spanwise flow on the aerodynamics of the devices are not known. These effects are likely to decrease effectiveness (lead to larger size) but not change the basic conclusions.

In view of this last conclusion, it is apparent that more work must be done to identify the aerodynamic performance of these devices in conditions that are representative of operating wind turbines. NREL is currently supporting two projects aimed at doing so. The first effort involves additional wind-tunnel tests to investigate higher Reynolds Numbers, roughness, and unsteadiness. These will be conducted on a pressure-tapped model of the NREL S809 airfoil using a spoiler-flap, a plain flap ("unvented aileron") and a vented plain-flap ("vented aileron"). The second effort involves the testing of these same devices on an experimental turbine at the National Wind Technology Center. The purpose of these tests is to validate the relative performance of the devices as observed in the wind tunnel, and to give designers greater confidence in these data for use in developing aerodynamic brakes for new rotors. Obviously, the final validation of these devices will come when they are incorporated into operating wind turbines, which will allow us to compare their cost and effectiveness to the traditional alternatives.

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