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COMPARATIVE WIND TUNNEL TESTS OF NACA 23024 AIRFOILS WITH SEVERAL AILERON AND SPOILER CONFIGURATIONS*

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ABSTRACT

This paper reviews research efforts at Wichita State University sponsored by NASA Lewis Research Center to design and evaluate aerodynamic braking devices which will be smaller and lighter than full-chord blade pitch control.

Devices evaluated include a variety of aileron configurations, and spoilers located at both trailing edge and near the leading edge. The paper discusses analytical modeling, wind tunnel tests, and for some configurations, full-scale rotor tests. Current designs have not provided adequate control power at high angles of attack (low tip-speed-ratios). The reasons for these limitations are discussed. Analysis and wind tunnel test data indicate that several options are available to the designer to provide aerodynamic slowdown without full-chord pitch control. Three options are suggested; adding venting in front of the control surface hingeline, using spoilers located near the leading edge, and using a two-piece control combining downward deflection inboard with upward deflection outboard.

NOMENCLATURE

c	section chord
c_d	section drag coefficient (drag/qc)
c_l	section lift coefficient (lift/qc)
c_n	section normal force coefficient (normal force/qc)
c_s	section suction force coefficient (suction/qc)
q	local dynamic pressure ($1/2* \rho *V^2$)
r	local blade radius
R	blade maximum radius
Re	blade chord Reynolds number, $V*c/\nu$
TSR	tip speed ratio, ($\omega R/V_{wind}$)
V	relative wind speed
V_{wind}	wind speed
α	angle of attack
ϕ	relative wind angle
ν	kinematic viscosity
ω	angular velocity

INTRODUCTION

One of the critical design requirements for wind turbines is to provide reliable methods for limiting rpm overspeed in the event of loss of load, or during high wind speeds. Mechanical brakes for this purpose become unacceptably large and heavy for large-scale horizontal-axis machines. Aerodynamic control of rotor overspeed may be accomplished by pitching the entire blade, in the manner commonly used for airplane propellers. The mechanism and structure required to accomplish this control become prohibitive on large rotors, however. As an alternative, a portion of the outboard span may be pitched to effect the desired control. This results in considerable weight saving, even though it requires locating actuators rather far from the axis of rotation. Since rotor torque varies approximately with the cube of the span, the outer portions of the blade produce most of the torque, and are therefore the portions along which control will be most effective. Virtually all current large scale machines utilize part-span pitch control, with the outer 30% being typical. These designs have been demonstrated to be quite effective. With this method of control, the movable section operates at moderate angles of attack, so that typical airfoil control data are adequate for design. Even though outboard panel pitch control has proven effective, it is desirable to further reduce the size, weight and cost of the control system.

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Airplanes have long used movable part-chord devices as effective means of controlling aerodynamic forces. Trailing edge "flaps" for producing added lift, or "ailerons" for modulating lift either positively or negatively for roll control, or "spoilers" for reducing lift to effect descent or roll control have all been used in this way.

This paper reports analyses and results of tests of a variety of control devices for wind turbines. Tests were conducted in the WSU 7' x 10' Walter Beech Memorial Wind Tunnel. Model for these tests was the NACA 23024 airfoil. A 9" chord was used so that large angles of attack (0^o to 360^o) could be tested without adverse wall interference. Reynolds number for most runs was 0.6×1^6.

AERODYNAMIC ANALYSIS

Strip Theory

The aerodynamics of the wind turbine rotor blade are analyzed by using strip theory, which considers the relative wind at each spanwise station on the blade, and resolves the aerodynamic forces produced on each airfoil-section strip of the blade. This technique follows the same line of analysis as traditional wing lifting-line theory, and is reasonably valid so long as substantial spanwise flow is not present. This approach permits the use of an extensive data base of airfoil design theory and data from 2-dimensional wind tunnel tests to design rotors, much as two-dimensional wind tunnel tests and strip theory were used by Orville and Wilbur Wright for their first propeller design. Figure 1 illustrates the strip method applied to a rotor, with pertinent velocities, force components and angles. This figure, which has been simplified by neglecting induced velocity effects, illustrates the relationship between relative wind angle, wind speed and rotor angular velocity. Figure 2 shows the variation of flow angle with spanwise position and TSR for an untwisted rotor. As shown, at high tip-speed-ratio (TSR), the flow angle will be relatively small, and conversely for low TSR the angles will be large. Therefore, during the initial phases of rotor slowdown, the angles will be small, but as the rotor rpm is decreased, the local flow angles will become large.

Airfoil Section Properties

Typical airplane wings operate over an angle of attack range from near zero to a few degrees beyond stall, which is usually below 20 degrees. Wind turbine rotors, by contrast, operate at angles of attack ranging from 90^{o} during start-up to to near zero degrees at normal operating rpm and wind speed. This means that an airfoil data base which may be quite adequate for airplane design, is often inadequate for wind turbine aerodynamic braking analysis. For this reason, high angle of attack wind tunnel tests have been conducted at Wichita State University for a number of airfoils, with and without control surfaces (Refs. 1 and 2).

As noted earlier, during normal operation, efficient wind turbine rotors are at relatively high TSR, with correspondingly small blade angles over the important outer portions of the blade. Many large-scale wind turbine rotors are designed with zero twist and zero blade angle out of the plane of rotation (beta) for ease of manufacture and structural simplicity. For these reasons, the present study is restricted to rotors with zero twist and zero beta. The velocity and force vectors in Figure 1 show that the pertinent aerodynamic force component which produces torque is the forward chordwise component, or "leading-edge suction" force. This force component and its companion component (normal force), are derived from lift and drag components by the coordinate transformation equations below:

$$c_s = c_l \sin(alpha) - c_d \cos(alpha) \qquad (1)$$

$$c_n = c_l \cos(alpha) + c_d \sin(alpha) \qquad (2)$$

For symmetric airfoils, c_l and c_d are approximately represented by the familiar relationships below:

$$c_l = 2 * PI * \sin(alpha) \qquad (3)$$

$$c_d = c_{do} \qquad (4)$$

Substituting (3) and (4) into (1), the following relationship results:

$$c_s = 2 * PI * \sin^2 (alpha) - c_{do} * \cos(alpha) \qquad (5)$$

While c_s is less familiar than c_l and c_d, it is the single parameter which governs blade torque. Since the function of aerodynamic braking devices is to produce zero or negative torque, these devices must provide zero or negative c_s over the required angle of attack range.

Typical Airfoil c_s Data

A typical c_s versus alpha plot is shown in Figure 3. This plot shows that there two regions of positive c_s, and therefore four angles of attack for which c_s is zero. This means that there are several equilibrium states for which the rotor torque is zero. In fact, consideration of the excess torque required to accelerate the rotor will illustrate that only the two states for which c_s is increasing as alpha increases are in stable equilibrium, and these are the possible operational "run-a-way" states. These characteristics were identified and discussed in reference 1. The first region of positive c_s is in the low-to-moderate angle of attack range, before separation and c_{lmax}. The second regime of positive c_s occurs at angles of attack above about 60^{o}. This second regime is primarily a result of the nose radius of the airfoil, and will be present irrespective of trailing edge control device, since the flow over the aft portion of the airfoil is separated for these angles. Fortunately, the equilibrium angle of attack for this state is so high that the rpm will be acceptably low, even for hurricane wind speed. Thus the design requirement for a control device is that the c_s remain negative for all angles of attack below about 60^{o}. The remainder of this study focusses on methods for achieving this goal.

Figure 4 shows c_s versus alpha curves for an airfoil without control and the same airfoil with 20% chord aileron and 20% chord trailing edge spoiler. Both aileron and spoiler produce adequate negative c_s at low angles of attack. An interesting characteristic of these curves is that as angle of attack is increased, the c_s shows a parabolic increase, as indicated by equation (6). This trend has been observed for virtually all configurations. The increase in c_s with alpha is nearly irrespective of airfoil and trailing edge control device, and continues until stalling occurs, as evidenced by simultaneous attainment of maximum values for c_l and c_s. While many configurations were tested which produced negative c_s for all angles below stall, all configurations of ailerons or aft mounted spoilers exhibited the steep c_s versus alpha relationship, with c_s approaching zero or becoming positive before section stalling occurred.

Reynolds Number Effects

While a number of control devices tested provided negative c_s for all angles of attack below 60^{o}, many of them exhibit a sharp peak in the c_s curve at the stalling angle of attack (typically 20^{o} to 30^{o}). It is well known that increase in Reynolds number will increase the stalling angle and c_{lmax} of most airfoils. Since large scale rotors will typically operate at Reynolds numbers higher than the wind tunnel tests, full scale hardware can be expected to have higher stalling angles, and consequently have positive c_s for some angles below the 60^{o} requirement. The non-linear character and high slope of the c_s curve makes the performance particularly sensitive to Reynolds number. Figure 5 shows data which illustrate how increasing Reynolds number results in positive c_s for a limited alpha range below 60^{o}. Rotors with this type control device will exhibit slowdown only to the zero c_s angle of attack, which may be at an unacceptably high rpm. Alternative methods for improving control effectiveness at high angles of attack are given in the sections which follow.

Effects of Venting

The problem identified with respect to the performance of trailing edge devices for aerodynamic control is that at angles of attack in the range of 20 to 30 degrees, the suction force tends toward zero, and may become positive for a limited angle of attack range before again becoming negative. Thus, what is needed is a mechanism to limit the c_{lmax} of the airfoil with upward deflected aileron. One possible means to limit c_{lmax} is to allow air to "leak" from the lower surface up to the upper surface at high angles. This is accomplished rather easily by providing a slot or gap near the deflector hingeline. A configuration can be designed with such a gap, which would be closed when the control surface is at zero deflection, and open for large deflection angles. Figure 6 shows wind tunnel tests of the effects of hingeline gaps, and illustrates that the gap is effective in the critical angle of attack range, without penalty to control effectiveness at low angles. While some performance penalty is noted at very high angles of attack, venting does provide improved performance at angles of attack near stall. Tunnel flow studies reveal that the flow through the slot is from upper to lower surface at low angles. At about 20 degrees, the flow direction changes, and flow is from lower to upper surface for angles of attack greater than 20 degrees. This leak flow evidently reduces c_{lmax} and therefore limits peak c_s. Limited higher Reynolds number tests indicate that the gap flow will reduce the sensitivity of the peak c_s to Reynolds number.

Wind tunnel tests by Templin and Rangi (Ref. 4 and Fig. 7) show similar trends, and indicate that venting is effective in reducing the suction peak in the 20^o to 30^o alpha range. Their data were obtained using an NACA airfoil, and are presented using a coefficient based on aerobrake chord rather than airfoil chord. Even though these results do not show positive suction in this regime, it is possible that increase in Reynolds number above the 1.7×10^6 test value or change of airfoil section could result in positive suction. Data from WSU tests for a similar double spoiler arrangement are shown on this plot for reference. The trend of the WSU data is strikingly similar to the NRC data, and illustrates that while the NRC data do not show positive c_s in this alpha range, higher Reynolds number might result in positive c_s. The comparison serves to point out the tendency for positive suction force for unvented control devices, and the advantage of venting.

Effects of Hingeline Location

As an alternative to large chord trailing edge control, spoilers with forward hingeline locations have been studied. Analytical studies have been conducted using a computational procedure developed by Dr. Alan Elcrat, professor of mathematics at Wichita State University, to analyze the effects of locating spoilers at various positions along the airfoil chord. A computer code has been developed for this purpose. This analysis uses a conformal mapping technique from potential flow aerodynamic theory to establish the inviscid flow pattern. Then theoretical aerodynamic forces associated with an airfoil plus spoiler are calculated. While the method currently treats the airfoil and spoiler as thin flat plates, the results are expected to reasonably predict trends for thick, cambered airfoils with spoilers, just as classical thin airfoil theory is known to properly predict trends of lift versus angle of attack for airfoils with thickness for angles below stall. The analysis results show interesting trends for spoiler effectiveness. The lift increments for given spoiler chord and deflection are relatively insensitive to hingeline location for zero angle of attack. On the other hand, as spoiler hingeline is moved forward, the c_l versus alpha slope is reduced as a result of the loss of suction pressures aft of the spoiler trailing edge. This should have the important consequence of reducing the sharp rise of c_s versus alpha, which should reduce the tendency for c_s to become positive for angles of attack below 60^o. This latter consideration is especially important for the case of large-scale wind turbine rotor design. Based upon these theoretical considerations, wind tunnel tests were conducted to evaluate spoilers at forward hingeline positions, at high angles of attack. The results of those tests are shown in Figure 8.

These test data show that the trends predicted by the theoretical analysis have been demonstrated. In particular, the negative c_s for a given spoiler chord and deflection at xero angle of attack is essentially independent of hingeline for zero angle of attack. However, the forward hingeline configurations are show much more effective at higher angles of attack. It remains to demonstrate that this performance can be achieved at the larger Reynolds numbers of full scale operation, and in the real environment of a rotating blade. It must be noted that locating spoilers near the leading edge of an airfoil poses special problems to insure that the power generating performance of the airfoil is not compromised due to gaps, hinges, poor fit, etc. Further, structural designers do not favor this location because of intrusions into the torsion carrying skin.

Combined Up and Down Controls

The undesirable characteristic of the upward deflected spoiler or aileron is that the suction becomes nearly zero or positive at high angles of attack. These high angles of attack occur over the portion of the span somewhat removed from the tip, that is, over the region from 30% to 60% span (see Figure 2.) Just as upward control surface deflection delays stalling angle, downward deflection results in early stalling and consequently in negative suction at high angles of attack. Thus, a downward deflected aileron on the inboard span will be fully stalled at the low tip-speed-ratios necessary for shutdown. Therefore, upward control deflection over the outer span could be combined with downward control deflection over the 30% to 60% span region. The outboard control would provide adequate control at high TSR values. As TSR is reduced for shutdown, the inboard control would be deflected downward to provide positive aerodynamic braking over this portion of the blade. This concept, while more complex than a single control surface, is promising enough to merit further consideration.

ROTOR TESTS

Large-scale tests of aileron-type control devices have been conductd by NASA Lewis researchers at the Plum Brook site, using the 125 ft. diameter MOD-0A machine. These results are reported in more detail in a separate paper, but selected results are shown here. Figure 9 shows equilibrium rpm versus wind speed from full-scale tests of the NASA MOD-0A turbine with 20% chord aileron with 60° deflection, a simulated 30% chord aileron with 90° deflection, and approximate results for a 38% chord aileron with 90° deflection. Increasing the chord and deflection of the aileron results in additional slowdown, but the equilibrium TSR is still not as low as desired. The chord dimension of the control device might be further increased, but the disadvantage of this approach is that the cost of the control device, both in terms of size and weight, is increased. At some point, the control device may become as expensive as the full-chord pitch control it is designed to replace!

RESEARCH IN PROGRESS

WSU has a small (20-inch diameter) rotor test rig fitted with dynamometer for torque and thrust measurement. This rig has been used for rotor wake and flow visualization studies, and is currently being used for evaluation of spoiler hingeline location effects. While the small scale provides only very low Reynolds number data, the rig is useful in that rotational effects are present.

Reflection-plane wind tunnel tests are planned at WSU to evaluate the section characteristics of a 30% control device with large (5-10% chord) venting. It is believed that this design will provide adequate control throughout the angle of attack range, with aerodynamic balance to reduce control actuator requirements. Twenty-inch rotor tests are planned for this device to further evaluate it in a rotating environment.

CONCLUSIONS

1. Wind tunnel tests, full-scale tests, and analysis have revealed problems associated with the design of part-chord control devices at high angle of attack.

2. Three concepts for improving control effectiveness have emerged from the present studies:
   (a) Hingeline venting added to an upward deflecting 30% chord control device.
   (b) Spoilers with forward hingeline locations.
   (c) A two-control system with outboard aileron deflected upward and inboard aileron deflected downward.

3. Evaluation is continuing for all three concepts above.

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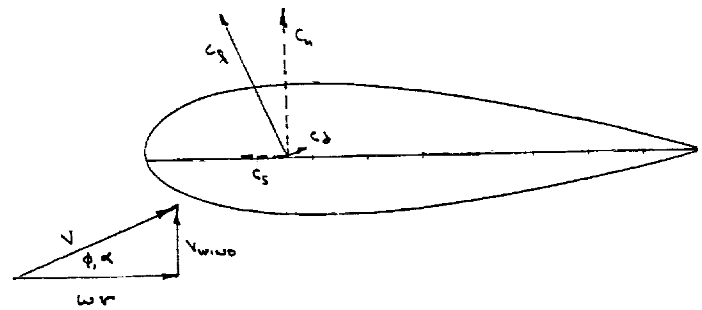
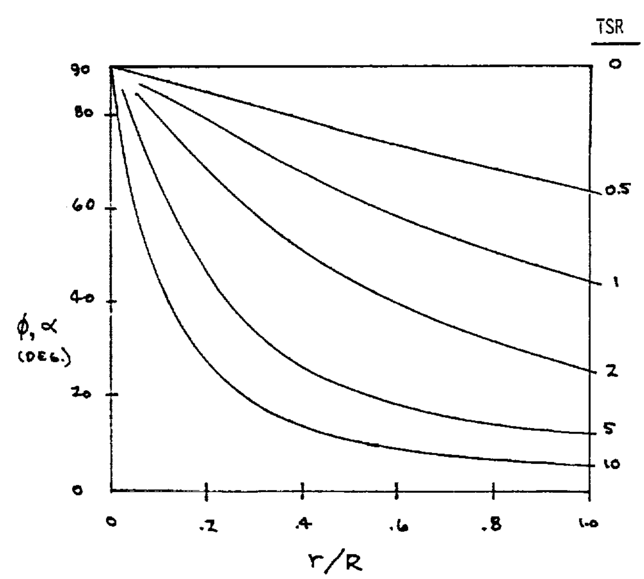


FIGURE 1 - ROTOR VELOCITY AND FORCE COMPONENTS



FIGURF 2 - ROTOR FLOW ANGLES

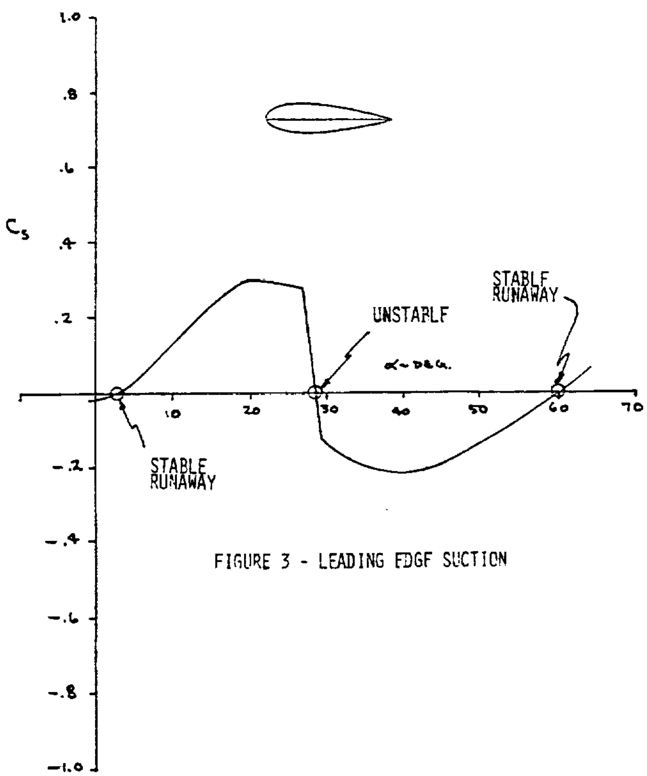


FIGURE 3 - LEADING EDGE SUCTION

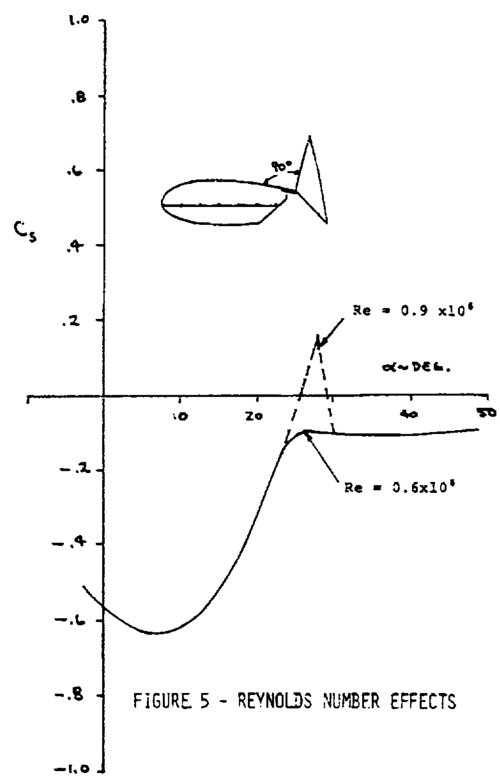


FIGURE 5 - REYNOLDS NUMBER EFFECTS

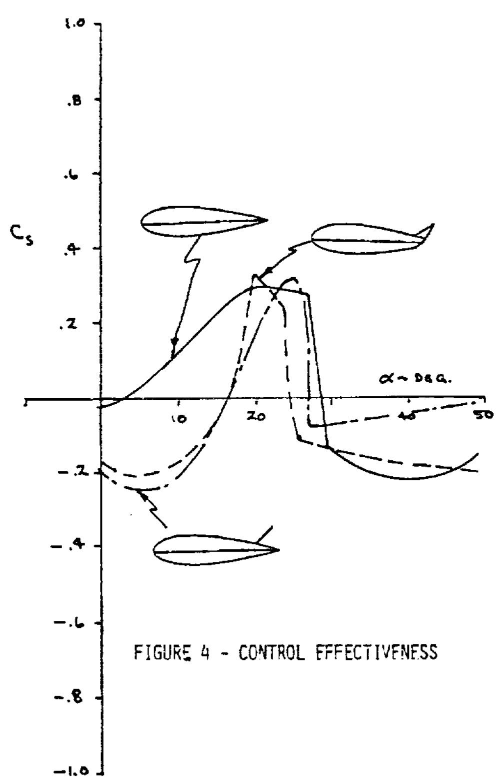


FIGURE 4 - CONTROL EFFECTIVENESS

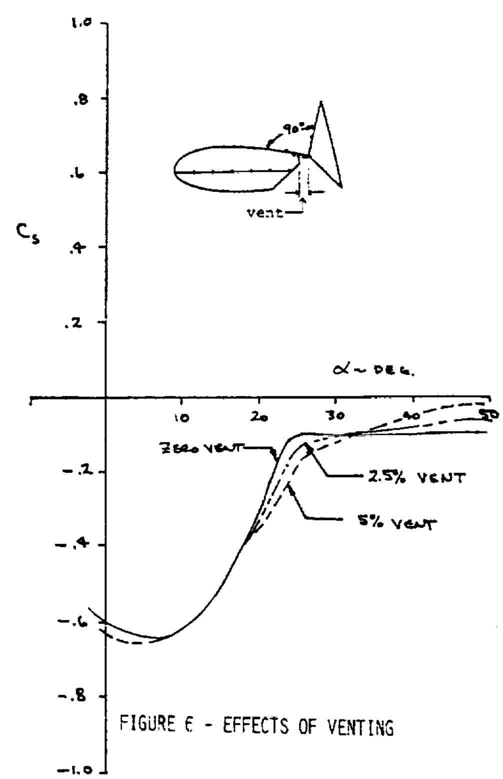


FIGURE 6 - EFFECTS OF VENTING

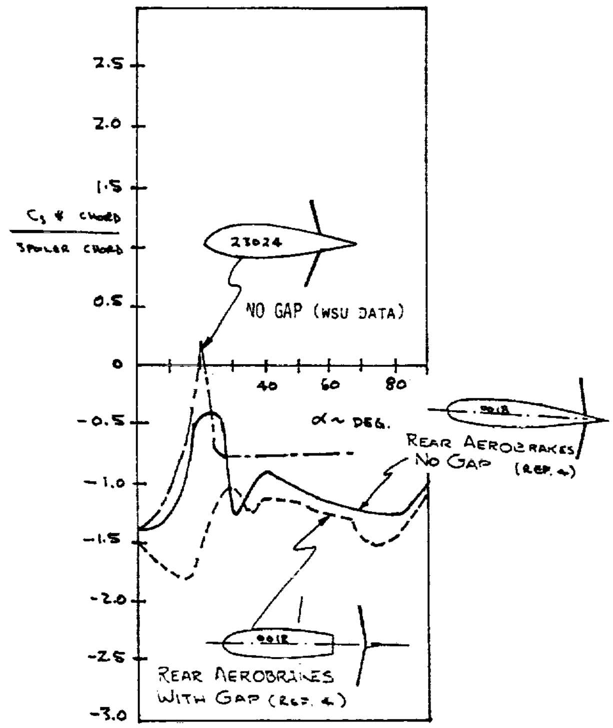


FIGURE 7 - NRC TESTS WITH VENTING

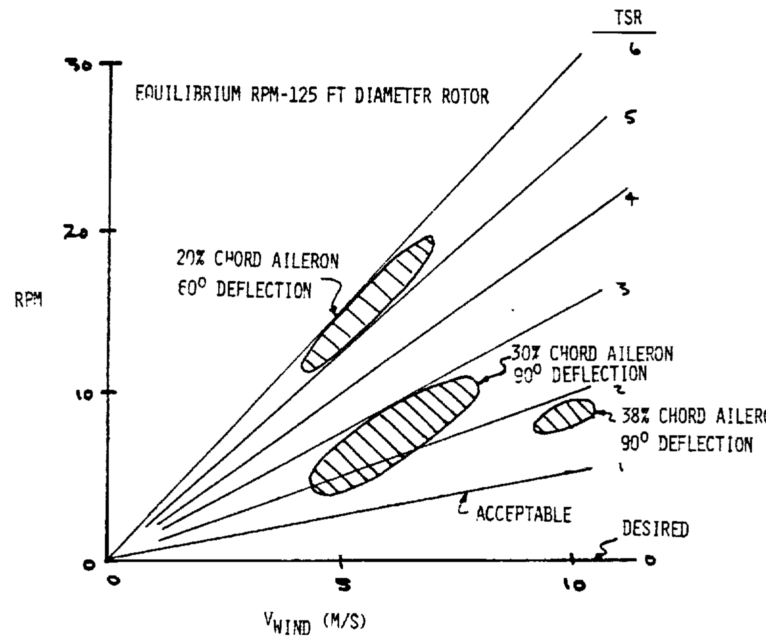


FIGURE 9 - LARGE-SCALE ROTOR CONTROL

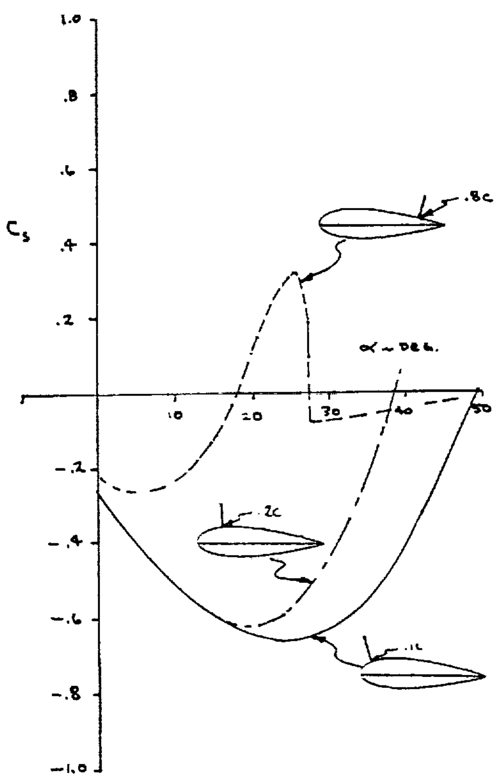


FIGURE 8 - EFFECTS OF HINGELINE LOCATION