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ANALYSIS OF A FIXED-PITCH X-WING ROTOR EMPLOYING LOWER SURFACE BLOWING

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ABSTRACT

Lower surface blowing (LSB) is investigated as an alternative to the variable blade pitch requirement for the X-Wing Circulation Control (CC) rotor concept. Additional trailing edge blowing slots on the lower surfaces of CC airfoils provide a bi-directional lift capability that effectively doubles the control range. The operational requirements (aerodynamic environment) of this rotor system are detailed and compared to the projected performance attributes of LSB airfoils. Analysis shows that, aerodynamically, LSB supplies a fixed-pitch rotor system with the equivalent lift efficiency and rotor control of present CC rotor designs that employ variable blade pitch. Aerodynamic demands of bi-directional lift production are predicted to be within the capabilities of current CC airfoil design methodology. Emphasis in this analysis is given to the high-speed rotary wing flight regime unique to stoppable rotor aircraft. The impact of a fixed-pitch restriction in hover and low-speed (transition) flight is briefly discussed.

INTRODUCTION

Present CC rotor V/STOL designs such as the RSRA/X-Wing rotor (Linden and Biggers, 1985) incorporate a variable mechanical collective blade pitch mechanism primarily to enable lateral moment trim in high-speed rotary flight. This mechanism, together with the additional structural weight associated with controllable pitch, constitutes a significant portion of the lifting system weight. Thus, it is desirable to extend the aerodynamic capabilities of CC rotors to allow a fixed, zero collective pitch rotor design. The work presented is the initial analytical investigation of one proposed route to this design goal; specifically, application of the LSB concept wherein slots are provided on the lower surfaces of the rotor blades for production of negative incremental lift when needed for moment trim.

BACKGROUND

For conventional helicopters, the blade pitch is varied in a cyclic manner about some mean or "collective" value (Θ_c) to effect rotor thrust and moment trim. The pitch angle is cyclically varied inversely to the dynamic pressure (q) with lower pitch and, hence, lower lift coefficients on the advancing side of the rotor disc. Figure 1 illustrates present CC rotor designs that yield comparable cyclic modulation of lift by operating with a low--even negative--collective pitch setting (typically -5 deg at high speed) and by cyclically varying the level of positive augmented (or blowing) lift. The necessity to achieve low C_ℓ's on the advancing side of the rotor disc requires the negative blade pitch, which penalizes the lifting potential elsewhere on the disc. The advantage of LSB is that low C_ℓ's can be produced in the high q region while operating with a zero collective pitch setting (fig. 1).

A fixed-pitch rotor design would have the advantage of simplified hub design and reduced weight. Weight savings are realized by (1) eliminating the collective pitch actuator hardware, (2) simplifying the rotor head structural design, and (3) integrating the hub fairing with the blade contour. These design changes would also contribute to improved aerodynamic performance by reducing the adverse effects of blade/hub vortices produced by the discontinuity at the blade root/hub fairing interface.

The notion of using dual slotted (upper and lower surfaces) CC airfoils to produce either positive or negative lift is not novel. Kind and Maull demonstrated the application of this concept in 1968. In addition, Ham et al. (1974) applied this airfoil configuration to a gust generator apparatus used in wind tunnel studies.

DESIGN DESCRIPTION

The CC airfoil configuration used in this investigation is shown in figure 2. Here, in addition to the two upper surface blowing (USB) slots commonly associated with high-speed CC rotor designs, a third slot is included on the lower surface trailing edge of the airfoil. For the present study, the elastic properties (slot height versus duct pressure) of the three slots are assumed to be identical. Such an airfoil can optionally have air supplied to the lower duct only, which produces a lift increment in a direction opposite to that of normal CC airfoil operation. There is no requirement for an additional lower surface slot at the leading edge for the purpose of producing roll moment trim in the rotary mode.

The sophistication of representing the pneumatic system with an additional duct and blowing slot required that a simplifying assumption be made in the control philosophy. In the analysis, therefore, the upper and lower surface pneumatic control inputs were coupled so that only one trailing edge slot per blade is blown instantaneously. This is convenient because no changes are required in the current trim control logic, and modeling of the performance behavior of simultaneously blown upper and lower surface slots is avoided. Figure 3a shows the pneumatic control inputs used to trim a representative LSB rotor in conversion at an advance ratio (μ) of 0.85, which is the critical flight condition in terms of rotor lift capability as discussed by Schwartz (1984). The upper surface slot is blown by a sinusoidal control wave with peak pressure truncated at the maximum level of a typical pneumatic supply system. Pressures on the advancing side of the rotor disc descend below the level required to open the flexible slot thereby leaving it closed over a wide azimuth range. The lower surface control wave is also sinusoidal and varies inversely to that of the upper surface. The proximity of the lower surface duct pressure level to that of slot closure is a constant multiple of the proximity of the upper surface pressure to the slot closure value. Thus, strong LSB is used over portions of the disc where the upper surface is unblown; see figure 3a.

The portion of the blade span over which the lower surface slot extends affects the pneumatic control inputs required for trim. Figure 3b shows the control waves necessary to trim a partial-span LSB rotor design to the same thrust level as that of the full-span design (fig. 3a). In figure 3b, the lower surface slot extends over the outer 30 percent of the blade span. Because LSB is applied over a smaller spanwise range, higher blowing pressures are needed over a wider azimuth range. Note that partial-span LSB leaves a significant portion of the inboard span completely unblown on the advancing side.

EVALUATION APPROACH

The airfoil performance requirements with regard to lift production of an LSB rotor system were not evident at the outset of the investigation. Whether the operational demands of such a system would be conducive to a convergent airfoil design process was uncertain. One objective of this investigation, therefore, is to determine if a given LSB airfoil can be sufficiently effective in producing high positive lift in one aerodynamic environment while providing for sufficient negative lift in another, possibly vastly different, environment. A recursive approach was used to evaluate the suitability of using LSB airfoils in place of variable collective pitch for CC rotor control. In lieu of any relevant LSB airfoil experimental data, an initial conservative representation of LSB airfoil performance was adopted. Use of this representation in the rotor design codes permits identification of the airfoil operating requirements (aerodynamic environment in terms of incidence, Mach number, etc.). The airfoil performance map is then reevaluated with regard to the operational demands of a zero-pitch rotor system to determine the impact of the assumed representation.

AIRFOIL PERFORMANCE REPRESENTATION

Conceptually, the operational lift envelope of an LSB airfoil is greatly extended beyond that of current CC airfoils; see figure 4 for uncambered section. Incremental blowing produces an identical absolute level of incremental lift, if applied in the opposite direction and at an angle of attack of opposite sign. The control range of the LSB airfoil, therefore, is effectively doubled, and high negative C_ℓ's can be produced upon demand.

One limiting factor to this idealized (symmetric) performance is the effect of camber, which is common to all current CC rotor designs. Camber is used to partly shift the chordwise loading distribution to midchord. This is desirable to lessen the effects of steep adverse pressure gradients produced under high loading conditions that can cause stall at relatively low angles of attack. In the case of lower surface blowing, the flat lower surface of a positively cambered airfoil does not provide loading relief to the leading and trailing edges. In fact, the tendency of the loading to be concentrated fore and aft is intensified. Premature stall could result, which would limit the performance envelope.

Theoretical pressure distributions for a typical CC contour at a nominal absolute lift level and zero angle of attack are compared in figure 5 for normal blowing (upper surface) and lower surface blowing. Abramson and Rogers (1983) tentatively established that the limiting criterion for lift due to blowing is the proximity of the trailing edge pressure coefficient level to the value corresponding to sonic velocity (C_p^*) on the Coanda surface. In the normal blowing mode, camber serves to minimize loading in the aft region thereby delaying the occurrence of C_p^*. Without the redistribution of loading due to camber and because the lift due to camber acts adversely (positively), in the LSB mode a higher level of blowing is required to achieve the same absolute net lift. Also, the loading is concentrated fore and aft, which results in C_p levels that approach the critical value much sooner. The existing X-Wing airfoil series was analyzed in this manner to establish performance boundaries.

Over the full range of operational Mach numbers (fig. 6), the absolute lifting potential of a typical cambered contour is lower when blowing is applied to produce a negative lift increment. However, with regard to the lift increment $(\Delta C_\ell = C_\ell - C_\ell \big|_{c_\mu=0})$, the difference is smaller. This variation in lift capability between the two modes of operation was modeled in the rotor design codes. For this study, it is further assumed that incorporation of the lower surface slot does not degrade upper surface blowing characteristics.

A word of caution is appropriate at this point. Results of experimental investigations indicate that if a strong shock wave is present just upstream of a slot, the airfoil capability to augment lift by blowing is substantially reduced. Thus, LSB may not provide the anticipated level of control in those regions of the rotor disc where the local Mach number exceeds approximately 0.75 to 0.80, depending on airfoil geometry. The rotor designs in this study do not experience these speeds; however, it is imperative that experimental LSB airfoil data be obtained in transonic flow conditions to permit high-confidence design of LSB X-Wing rotors intended to convert at high flight speeds (greater than 200 knots).

ROTOR/AIRCRAFT PERFORMANCE

Disc loading distributions for several CC rotor designs operating at the critical advance ratio for the same thrust level are shown in figure 7. These cases are all trimmed to a negligible roll moment. Figure 7a is a typical distribution for a variable collective (without LSB) design. The concentrated loading fore and aft and in the reverse flow region, along with a region of negative loading outboard on the advancing side, are characteristic of high-speed rotary flight. The latter feature is the result of the negative collective pitch setting required to reduce lift on the advancing side for roll moment trim. In this azimuthal range where little blowing is used, lift arises primarily from angle of attack and camber.

Figures 7b through 7d show disc loading distributions for LSB designs in which the lower surface slot extends over varied portions of the blade span. For the full-span LSB case (fig. 7b), a region of negative loading extends from root to tip in the second quadrant. Maximum blowing is applied to the lower surface slot at 90-deg azimuth where it is most effective for lateral moment production. However, as seen by the positive loading over the outboard, high-q region, LSB is not sufficient to completely overcome the basic goemetric (camber plus incidence) lift. (The geometric advancing incidence is +4 deg due to nose-up rotor attitude.) Figure 7b also depicts the steep nature of the azimuthal loading gradient, especially as the blade leaves the negative loading region. Here, the entire span is subjected simultaneously to a rapid change from lowest to highest loading, which may have implications with regard to vibratory forces (no higher harmonic control is used in this study).

As expected, if the lower surface slot is limited to smaller outboard span regions (figs. 7c and 7d), the negative loading becomes concentrated on a small spanwise region near the blade tip. Inboard, an area of high positive lift develops at ψ = 90 deg. This high lift is produced by nonblowing lift forces because neither upper or lower slots are blown in this region.

In addition to comparing LSB rotors with other current CC rotor designs, the benefits of LSB over other methods of achieving fixed-collective incidence designs is of interest. First is consideration of operating current rotor designs (without LSB) at a fixed, zero pitch setting. For a fixed-collective rotor design without LSB, the problem of achieving trimmed flight at high speed becomes a tradeoff between collective pitch and rotor shaft/disc angle settings. The rotor disc angle is crucial for optimized performance in terms of lift-to-power ratio, since the axial component of the high forward speed contributes greatly to the mean incidence experienced at the blades. As the blade pitch setting is increased toward zero deg, the rotor disc angle must be decreased from the typical 4- to 6-deg noseup attitude where the rotor operates in a near auto-gyro state. This trimmed disc angle reaches -2 deg (nosedown) for a zero collective pitch setting. At this rotor attitude, available blowing is not sufficient to overcome the decreased lift due to lower incidence. Figure 8 shows the predicted relative loss of rotor lift capability when this fixed collective pitch restriction is imposed on current CC rotor designs. Moreover, these high-speed V/STOL designs rely on substantial hub/fuselage, incidence-related lift forces, and the fuselage attitude must match the rotor disc angle (within 1 to 2 deg) due to rotor/fuselage proximity. Therefore, an aircraft with a current CC rotor set at zero blade pitch experiences greatly reduced net lift capability.

Conversely, when LSB is applied to a zero collective pitch rotor, the required trim control range is achieved without compromising the efficient rearward tilt of the rotor disc. Not only does the rotor produce equivalent lift, but the nonrotor lifting surfaces also retain their lift capability; see figure 8. Furthermore, as expected, no loss in rotor efficiency is experienced with the LSB design because the power required from the rotor and the compressor is equal to that required by a variable collective pitch rotor at the critical advance ratio.

ALTERNATIVES TO LSB

Other methods of providing cyclically varying control forces for high-speed trim of a fixed-pitch rotor system were briefly investigated. At zero collective pitch, the control forces must be sufficient to counteract a rotor thrust offset equal to approximately 25 percent of the disc radius (offset = moment/thrust/radius). One suggested method uses a modulated high velocity jet at the blade tip to produce a reaction force in opposition to the normal lift direction. Basic calculations show that the airflow requirements for the reaction jet far exceed (by about 400 percent) the output available from a compressor sized for the normal boundary layer control function.

Activation of leading edge (upper blade surface) slot blowing on the advancing side of the rotor often is suggested as a means of spoiling lift. Unfortunately, blowing in opposition to the local flow direction is not effective in producing negative lift increments, as shown in figure 9. The data, which are representative of the performance for the outboard portion of an X-Wing blade, show a negligible capability of leading edge blowing to degrade lift. Certainly, a mean ΔC_ℓ of -0.6, which is needed to produce the required offsetting moment for a zero-pitch configuration cannot be achieved with this technique.

Finally, the use of negative camber was considered as a substitute for a negative pitch setting in conversion. Aerodynamically, 1 deg of incidence is about equal to 1 percent of camber. Therefore, a reduction of the mean camber by approximately 5 percent is required for trim with a fixed zero-collective incidence setting. Such a design would have serious negative implications in hover. Indications are that none of these options are suitable alternatives for production of the required trim moments in high-speed flight.

ROTOR/AIRFOIL DESIGN IMPACT

A statistical analysis of the airfoil local operating environment yields insight to details of the airfoil design requirements for a particular rotor operating condition. By weighting parameters such as angle of attack by the absolute magnitude of the locally generated load, a mean productive value of the parameter can be obtained (Rogers et al., 1985). Figure 10 shows a comparison of the airfoil operating environments for three CC rotor configurations in conversion. For a variable pitch rotor (fig. 10a), the mean load due to blowing is constant along the blade span. Viewed in terms of total (net) load, the inboard section carries substantially more load than the outer regions. The magnitude of the inboard loading highlights the desirability of a blended blade/fairing contour (fixed-pitch design) to minimize the shedding of strong root vortices and improve hub/fuselage lift carryover.

This same rotor design, when forced to operate at a zero collective pitch setting (fig. 10b), operates in an environment of locally lower angle of attack. This is the cause of its inability to produce the required level of net lift with the given air compressor.

The mean local angle-of-attack distribution over the retreating side of an LSB rotor blade (fig. 10c) is quite similar to that of the variable pitch rotor. A majority of the total load is generated in the 0- to -10-deg alpha range. The mean spanwise loading distribution for this full-span LSB configuration is most revealing. Over much of the span, the mean lift due to blowing is negligible because negative incremental lift applied on the advancing side offsets the positive lift from blowing on other portions of the disc. Effectively, the blowing lift forces are being used primarily for cyclic rotor control with the net rotor lift arising from the higher blade incidence possible with LSB. Mean total loading is shifted outboard to resemble that of conventional rotors.

Further investigation of the local aerodynamic environment of an LSB rotor reveals important information concerning the design criteria of LSB airfoils. In figure 11, local airfoil incidence is shown versus local Mach number. Each symbol represents conditions at one of the 180 disc elements used in the analysis. Functional incidence is defined as alpha for conditions of upper surface blowing and as -alpha for LSB conditions. (This convention is used so that LSB operation can be intuitively viewed in the same familiar context as an "upper surface" slot.) The large excursions in angle of attack at low local speed are typical of high-speed rotorcraft operation due to large regions of low speed reversed flow and numerous tip path crossovers. Within the Mach regime where LSB is applied, the angle-of-attack range is narrow and relatively independent of M_∞. This range also generally coincides with the optimum angle of attack for CC airfoils to produce maximum lift increments. These analytical results suggest airfoil LSB mode design criteria that are quite concise and readily achievable in that the required operating envelope is limited to a narrow angle-of-attack band for all Mach numbers. Upper surface blowing mode operational requirements are similar to those of current variable pitch rotor designs.

The performance requirements of the airfoils for LSB operation and normal blowing are presented in figure 12 for trimmed, high-speed flight. The required lift increment for blowing is shown as a function of local Mach number for the 180 individual disc elements. In the higher speed regimes (0.3 to 0.7 M), where either upper or lower surface blowing may occur, LSB operation requires lift increments with absolute magnitude equal to or slightly greater than that of upper surface blowing. The incremental lift limit ($\Delta C_{\ell_{max}}$), however, is not reached at any disc location.

Tests of a CC airfoil family (the basic contour parameters of the airfoils are the same linear functions of thickness ratio) were recently conducted in a transonic wind tunnel. All of the contours were found to have the same peak value of the lift function ($\Delta C_\ell M_\infty^2$) and to differ only in the Mach number at which the peak occurs; see figure 13.

If an uncambered, LSB equipped airfoil is assumed to have the capability to produce equal absolute lift increments in both positive and negative directions, the empirical results from figure 13 can be compared to the analytically predicted lift requirement. Such a comparison is shown in figure 14, where elements corresponding to the outboard blade location ($t/c = 0.15$) are isolated from figure 12 and superimposed with the lift limits from figure 13. For USB operation at this span location, the lift limit is approached only at low speed where maximum blowing is applied on the retreating side of the rotor disc. The LSB feature is demanded precisely in the M_∞ regime where the absolute lift capability of the airfoil is maximum. Also, the magnitude of the negative lift increments required is well below the available levels. This match of required and available performance seems to exist over the entire span for this rotor design at the operating conditions examined. Implementation of the LSB concept, therefore, is well suited to the present CC rotor design so that modified, dual-slotted trailing edges can be retrofit to current contours for the purpose of concept demonstration.

OTHER OPERATING CONDITIONS

The relative rotor performance capability in hover, transition, conversion, and fixed-wing flight regimes is a major rotor design issue. While it has been demonstrated analytically that an LSB fixed-pitch design is a viable concept for CC rotor control in high-speed flight, the implications of this design at other operating conditions must also be examined.

Hover

In hover, the variable collective pitch feature of current CC designs is exploited by setting a positive blade pitch angle (typically, 6 deg). This yields optimum efficiency by using lift due to angle of attack generated by the higher mean local incidence to reduce the demand on the compressor. Hovering with a collective pitch setting of zero requires a higher blade pressure and, thus, compromises the rotor efficiency as expressed by the Figure of Merit in figure 15. Assuming that the projected missions of high-speed CC rotorcraft involve relatively short hover durations, it is feasible to accept this reduced hover performance. Note that the alternative of using negative camber for trim in conversion would result in further reductions of hover efficiency through the camber-θ_c equivalence.

Transition

For CC rotors, the available 1P-cyclic control authority is dictated by the proximity of the mean blowing level to the level corresponding to the maximum producible pressure. In transition from hover to rotary wing forward flight (10 to 50 knots), longitudinal moment control is critical. In this environment, a rotor with fixed, zero collective pitch requires a higher mean blowing level. This results in a lower available 1P-cyclic blowing control range than that of a variable pitch design. Analysis of transition flight for the present rotor geometry indicates that the mean pressure level required to maintain rotor lift precludes the use of LSB to augment cyclic control in this flight regime. Therefore, upper surface blowing alone must be capable of both overcoming the effects of reduced mean pitch and providing a sufficient longitudinal control moment. (Applying LSB in a higher harmonic mode to assist in transition flight may be possible, and should be addressed in future investigations.)

Fixed-Wing

Zero collective pitch is the standard control setting for steady, level flight in the fixed-wing mode. Because there is no cyclic control of blade pitch, any non-zero setting results in differential incidence between port and starboard wings. Blowing, then, must be used to trim the laterally unequal forces. Thus, the compressor consumes excess power (at a rate which is linearly proportional to the peak pressure supplied to the wings/blades), which decreases cruise efficiency. The use of differential blowing to achieve trimmed, level flight also diminishes the pneumatic control range available for maneuvering. Yet another inherent benefit of zero-pitch is that both sides of the rotor experience an identical aerodynamic environment. This minimizes the occurrence of roll moment disturbances caused by the differential encounter of nonlinear aerodynamic forces. With regard to these considerations, a fixed, zero-pitch design imposes no disadvantages in this flight regime.

SUMMARY

A fixed-pitch rotor has long been regarded as the ultimate goal of a stoppable rotor aircraft. The fixed collective advantage arises from the control and structural weight savings and from the increased freedom to integrate hub/blade

contours for maximum vehicle aerodynamic performance. Recent advances have been made in understanding and analytically predicting the geometry and Mach number related performance characteristics of CC airfoils. This insight has permitted the adaptation of present CC performance modeling to predict the impact of LSB implementation. This study has shown that dual-action airfoils employing lower surface, trailing edge slots provide an effective means of rotor control thereby eliminating collective pitch control without severely compromising rotor performance. Furthermore, the demands on LSB to produce moderate negative lift increments in a high-speed operating regime are well suited to the airfoil contours of current CC rotors. This indicates that current airfoils, when retrofit with LSB trailing edges, are suitable for an initial experimental investigation of LSB rotor characteristics.

REMARKS

Analytically, LSB offers an attractive alternative to "conventional" CC rotor design. Continued effort is being directed toward design and fabrication of a two-dimensional LSB airfoil model. Of major concern are the Coanda shape and blowing slot locations with regard to the projected operational requirements of both upper and lower surface blowing. The practicability of an LSB rotor system can then be assessed at low cost by modifying the RSRA/X-Wing model rotor pneumatic system and fabricating a set of LSB model blades. A logical extension of these efforts, of course, is to evaluate a full-scale zero-pitch LSB rotor system on the NASA Rotor Systems Research Aircraft.

ADMINISTRATIVE INFORMATION

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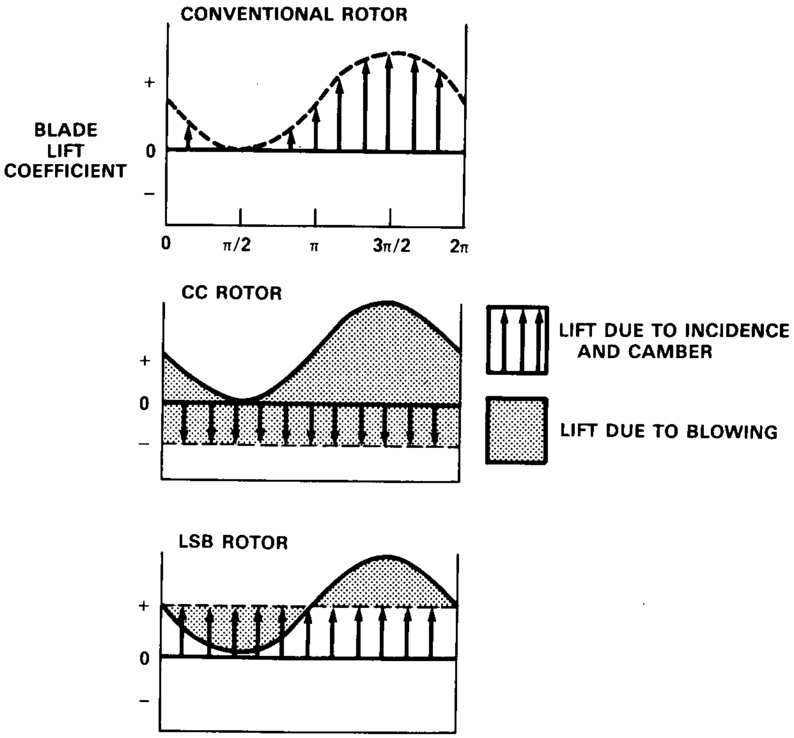


Figure 1.- Conceptual trim control methods for various rotor designs.

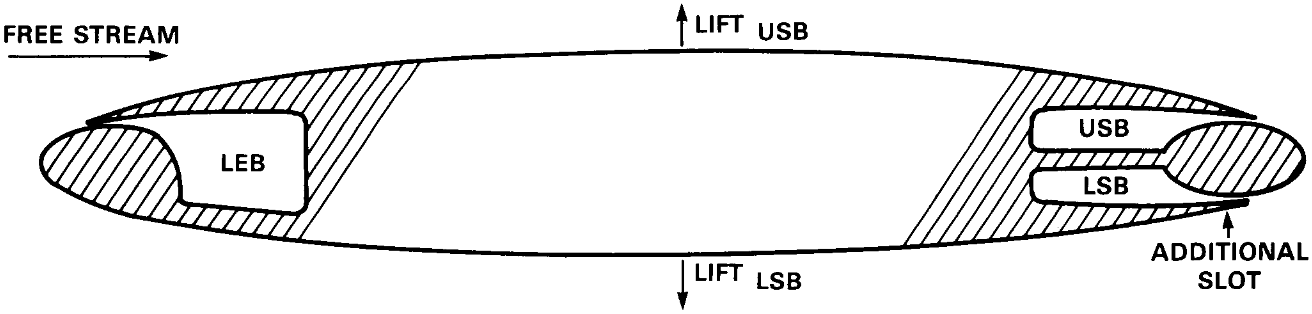
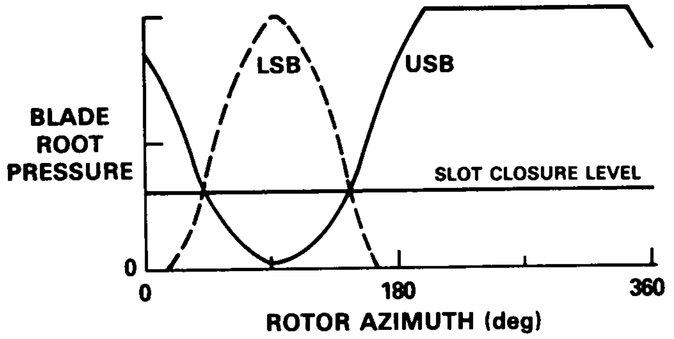
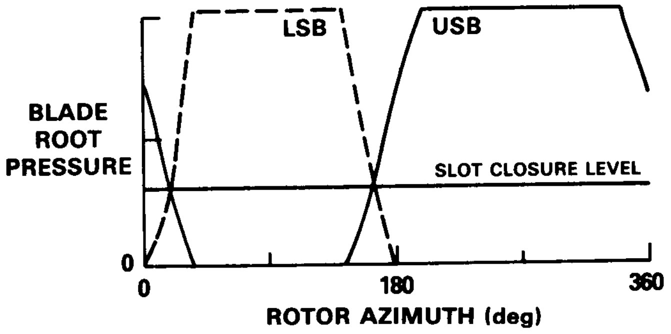


Figure 2.- Airfoil configuration for lower surface blowing.



(a) Full-span LSB.



(b) Partial-span LSB.

Figure 3.- Coupled cyclic control pressure waves.

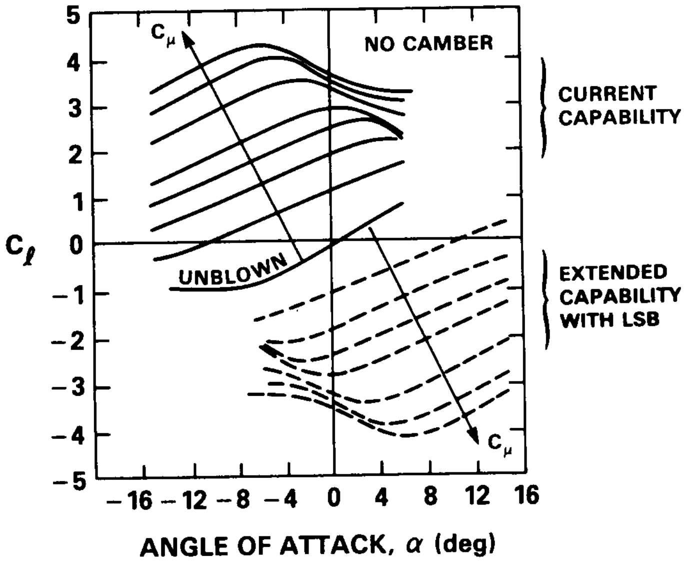
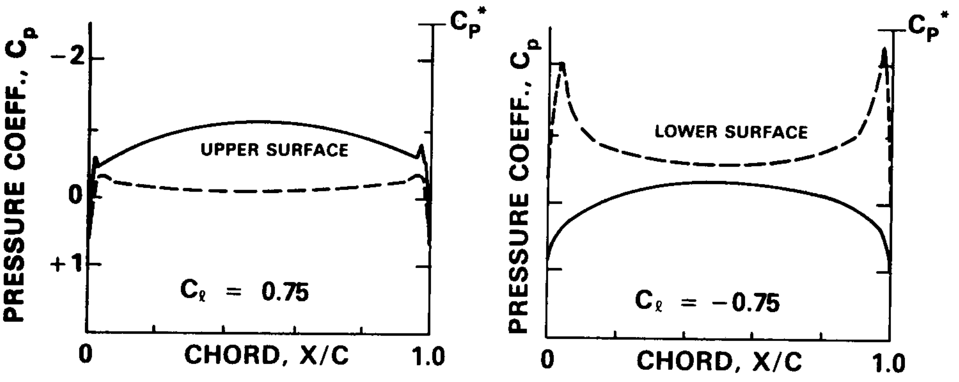


Figure 4.- Idealized lift control range for an LSB airfoil.



(a) Normal (upper surface) blowing. b) Lower surface blowing.

Figure 5.- Airfoil pressure distributions for absolute lift level (α=0 degrees).

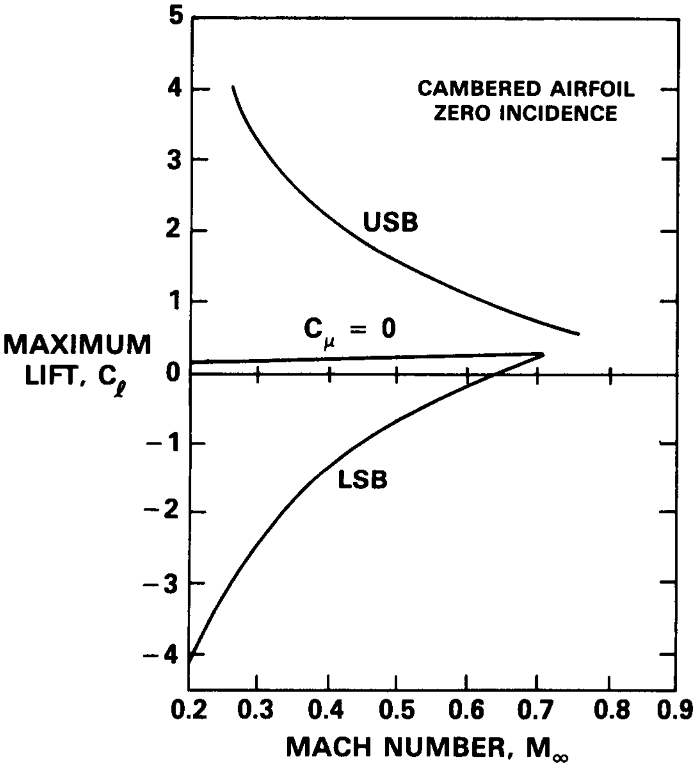
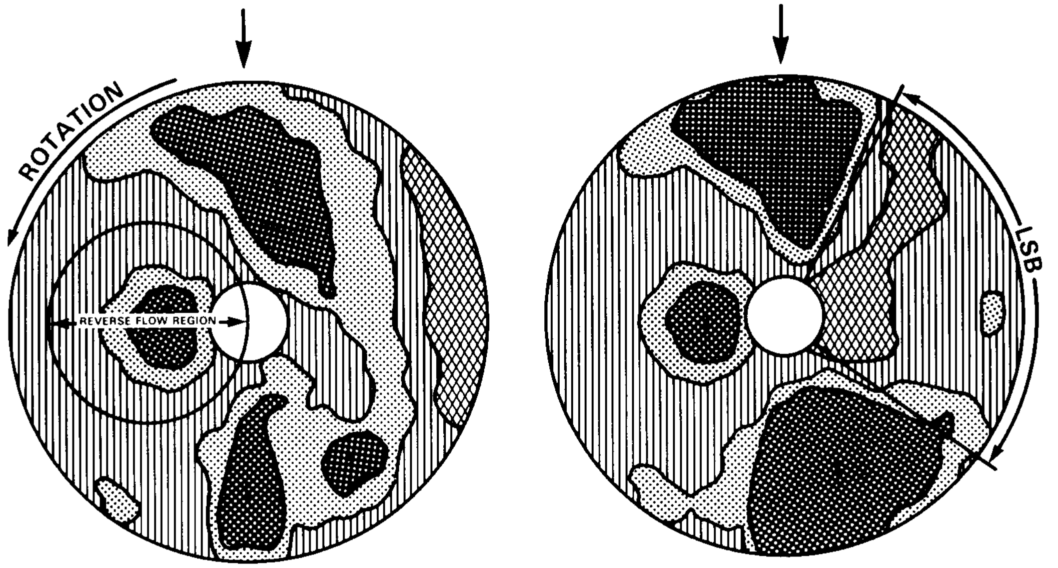


Figure 6.- Comparative influence of Mach number on airfoil theoretical lift capability.



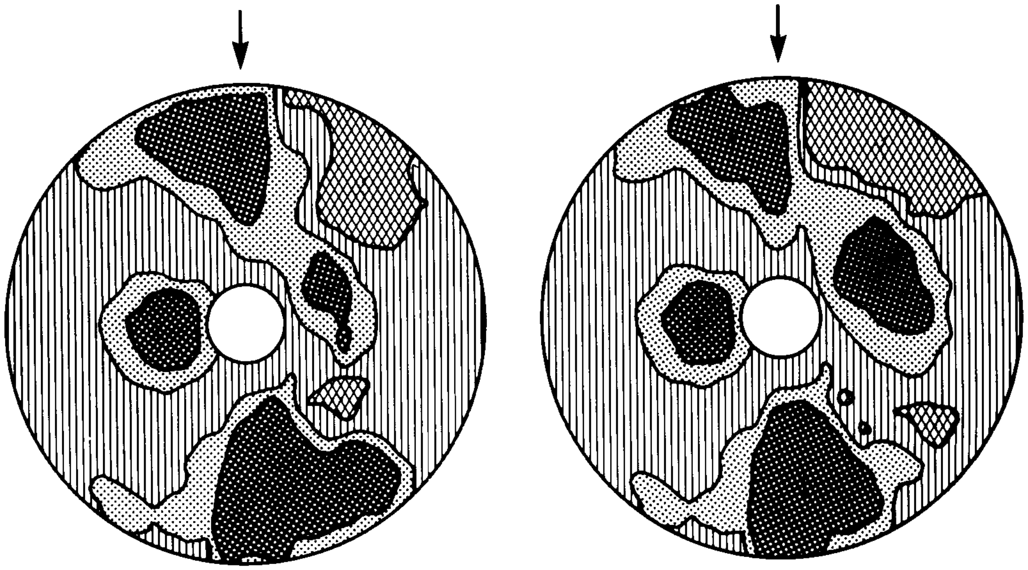
(a) Variable-pitch, advancing incidence $(\theta_c + \alpha_s) = -1$ degree.

(b) Zero-pitch, full-span LSB advancing incidence = +4 degrees.

$V_\infty = 0.85\ V_t$
1P CYCLIC TRIM
$C_T/\sigma = 0.12$
$\alpha_s = +4$ deg

$\frac{\text{LOCAL LIFT}}{\text{AVERAGE LIFT}}$

▩ 2 → 4
▒ 1 → 2
▥ 0 → 1
▦ −2 → 0



(c) Zero-pitch, partial-span LSB (0.5 r/R to tip).

(d) Zero-pitch, partial-span LSB (0.7 r/R to tip).

Figure 7.- Comparison of disc loading distributions for various CC rotor configurations.

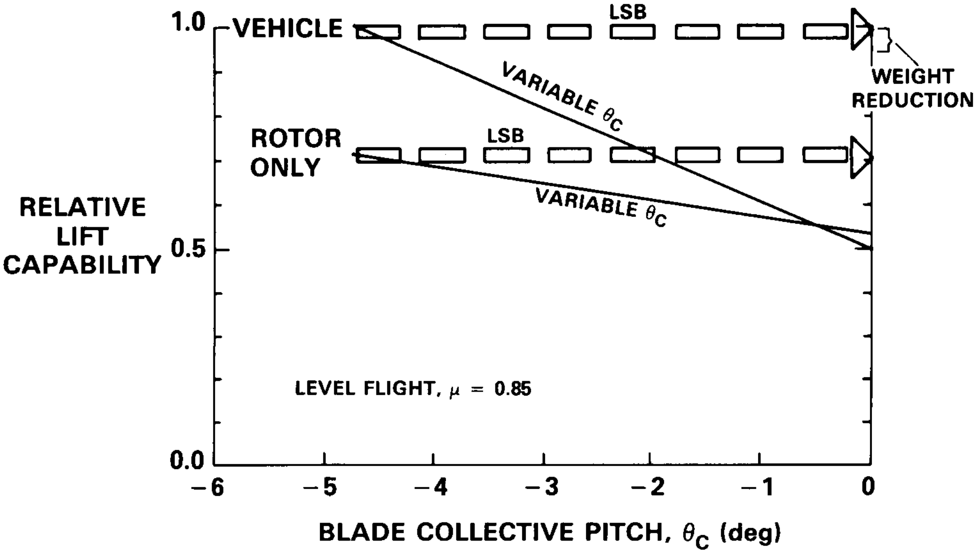


Figure 8.- Lifting performance comparison in conversion with variable collective pitch versus fixed-pitch (θ_c = 0 degrees, LSB).

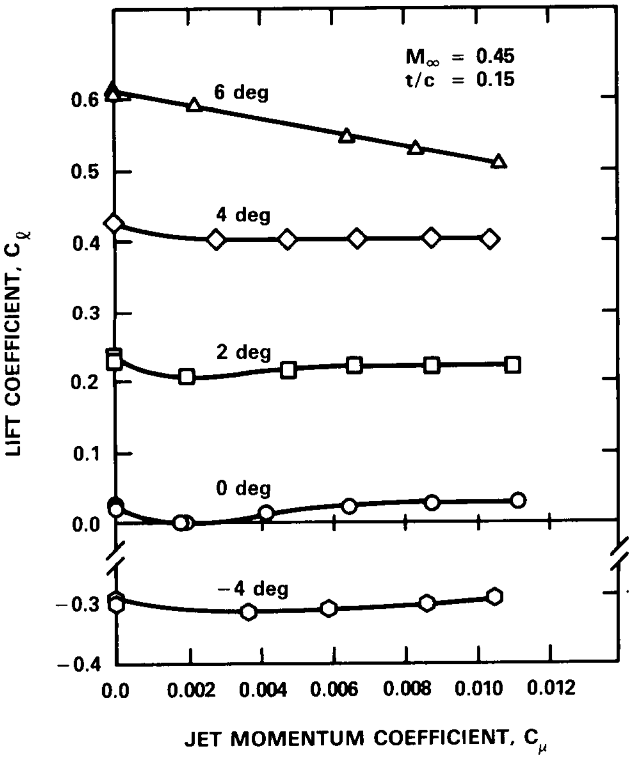
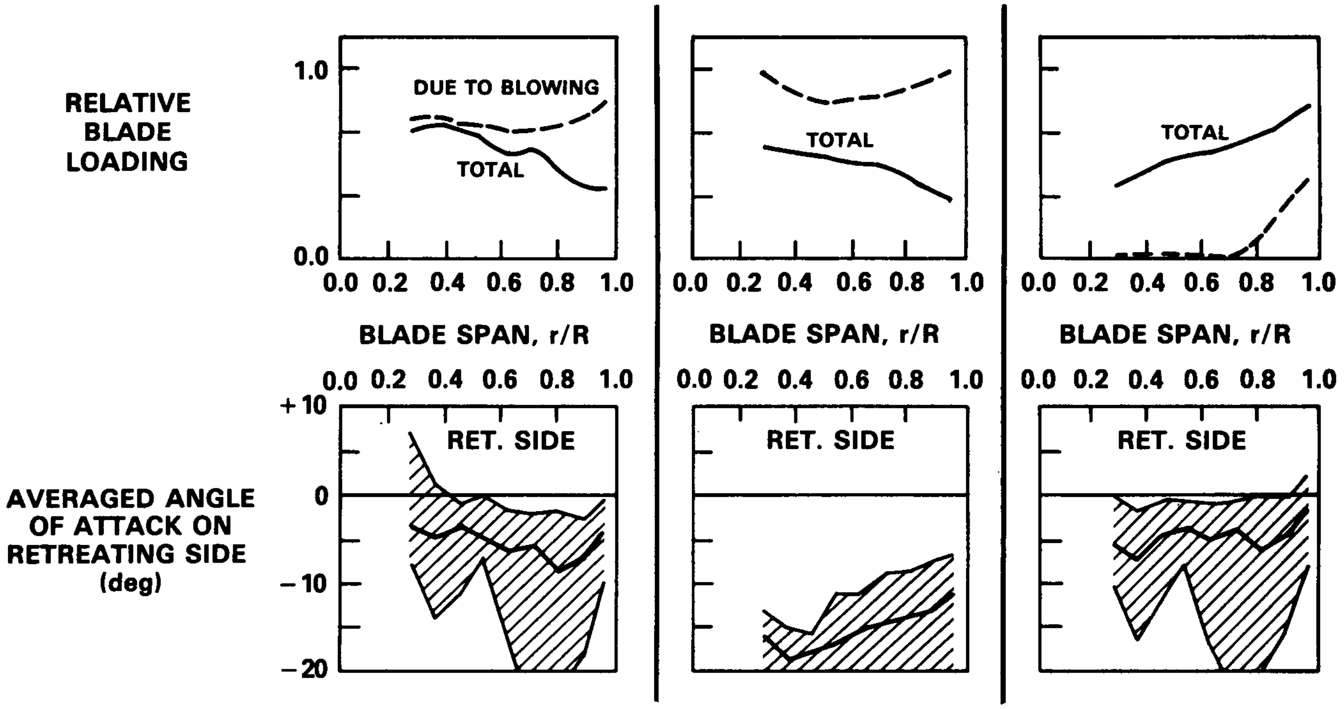


Figure 9.- Airfoil lift response to leading edge only blowing.



(a) Variable-pitch without LSB.

(b) Zero-pitch without LSB.

(c) Zero-pitch with LSB.

Figure 10.- Airfoil operating environment (azimuthally averaged) for variable pitch and fixed-pitch CC rotor configurations.

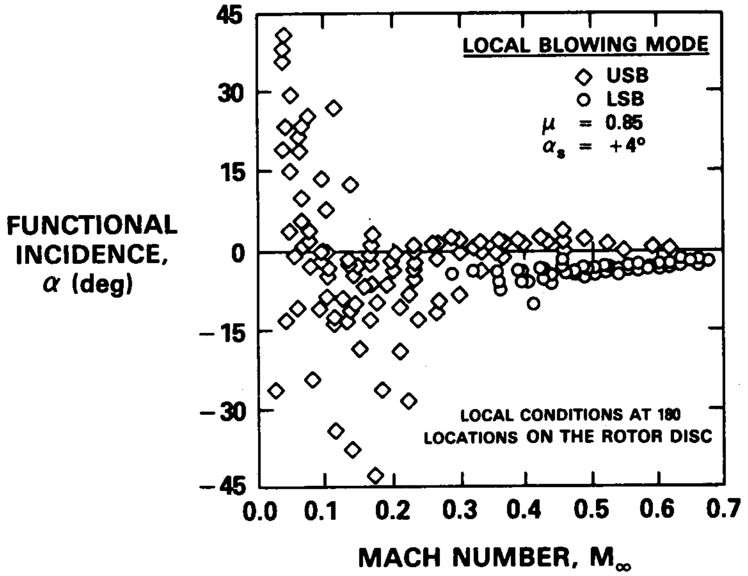


Figure 11.- Airfoil operational angle of attack for LSB rotor in conversion.

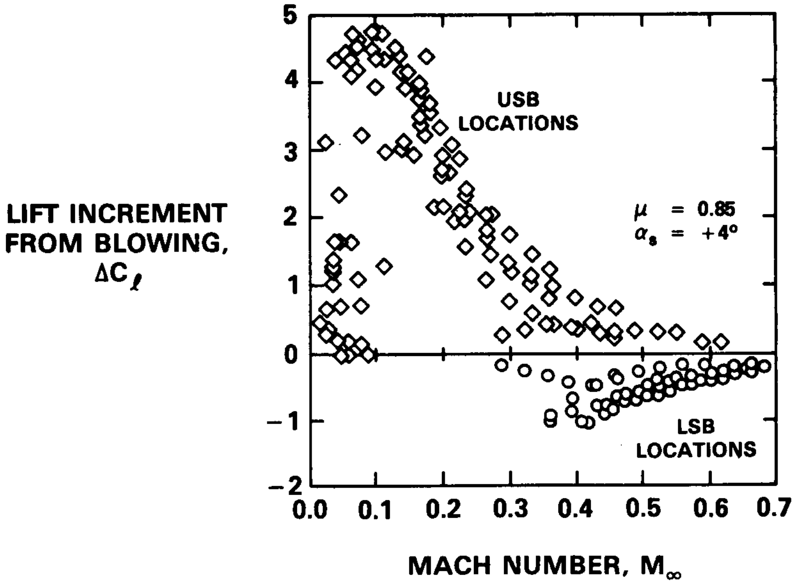


Figure 12.- Airfoil lift performance requirements for LSB rotor in conversion.

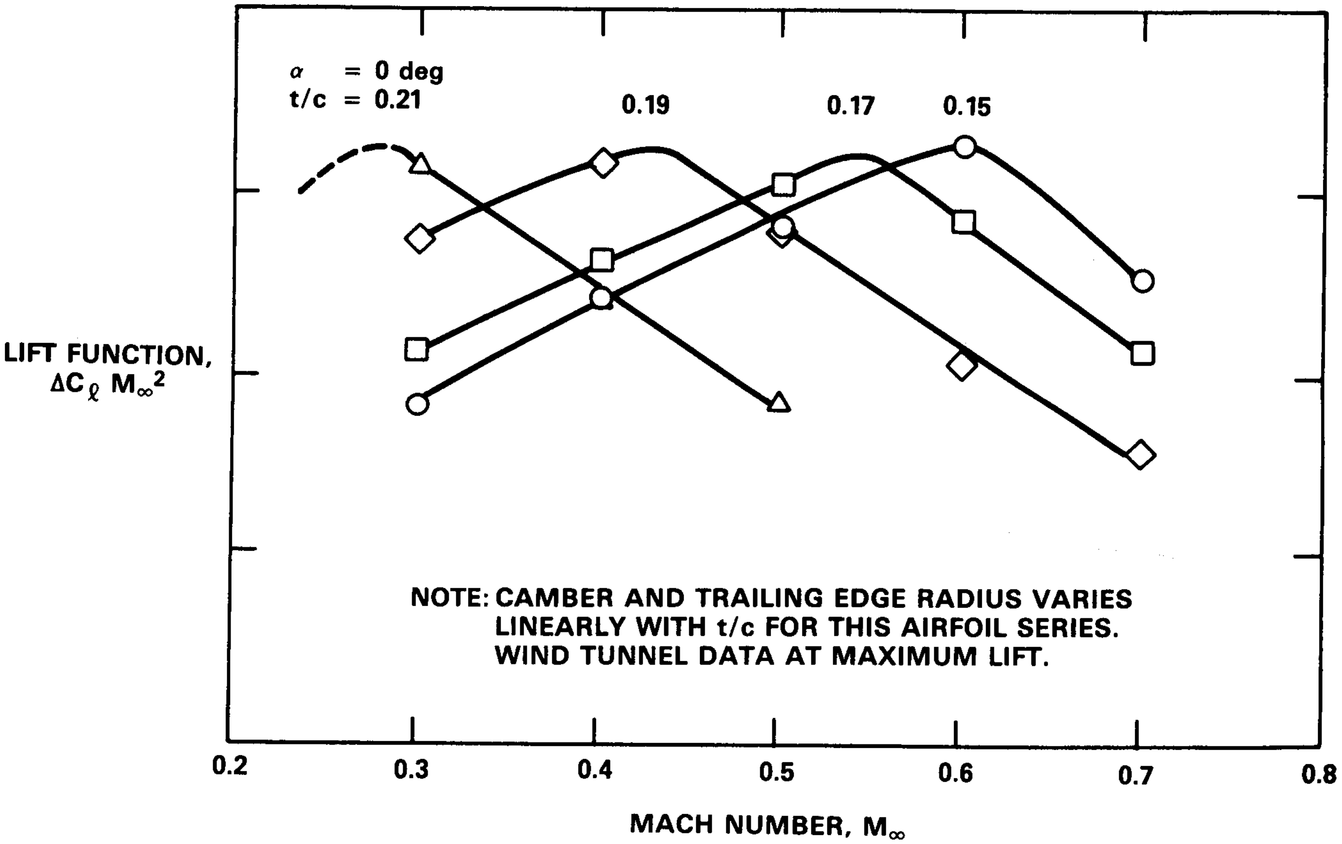


Figure 13.- Airfoil capability to augment loading at zero incidence.

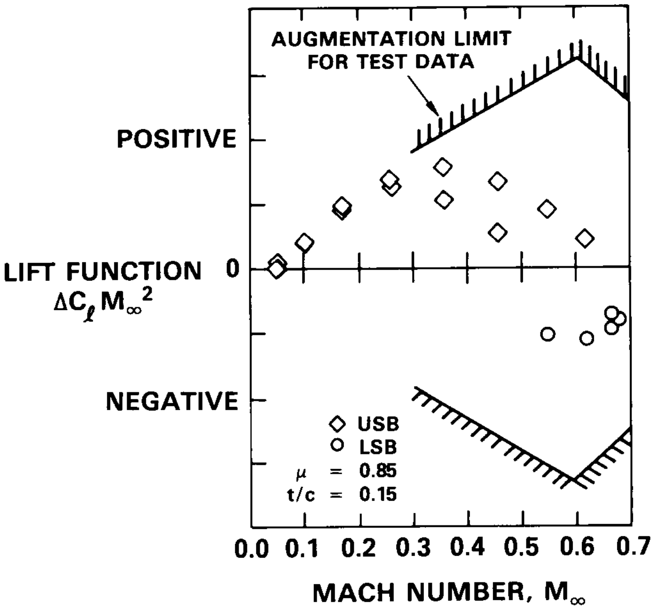


Figure 14.- Comparison of airfoil augmentation requirements and estimated performance limits.

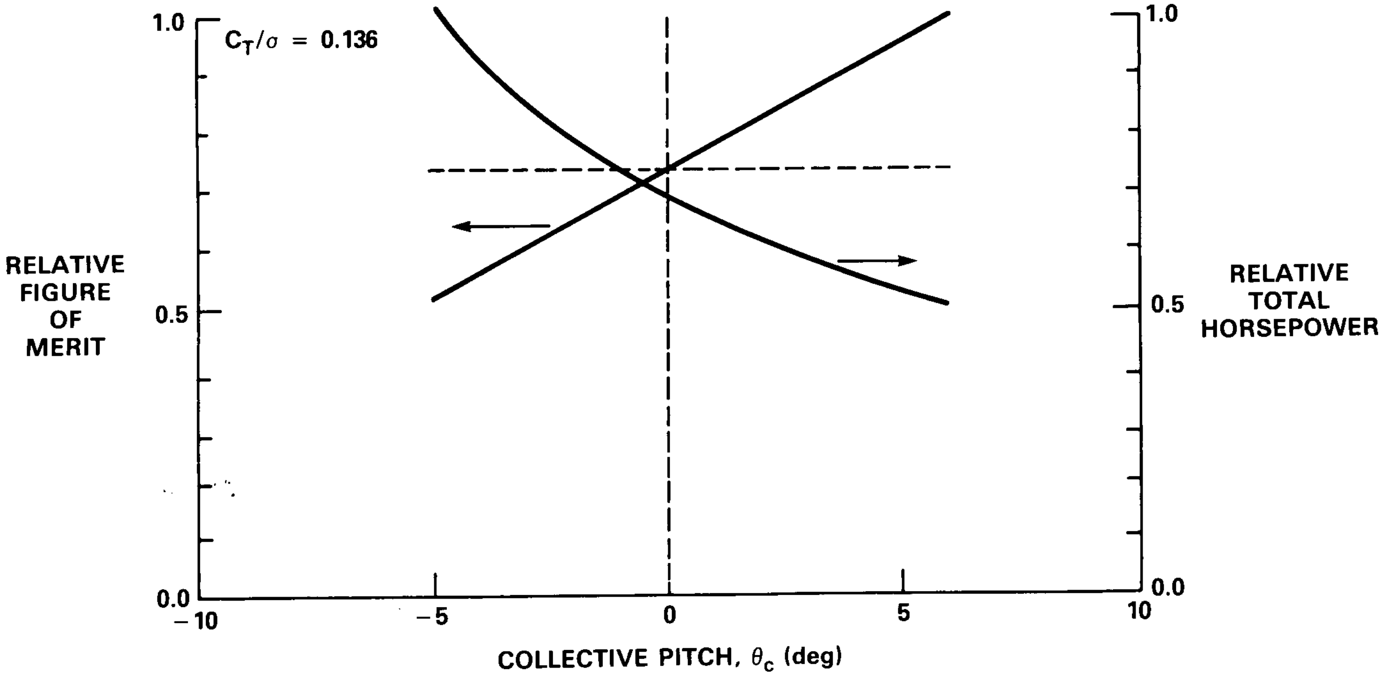


Figure 15.- Influence of collective pitch on CC rotor hover performance.