25. STATUS OF RESEARCH ON A SUPERCRITICAL WING

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SUMMARY

A drastic modification of airfoil shape for high subsonic cruise airplanes is proposed which substantially increases the drag rise Mach number. The airfoil incorporates a slot between the lower and upper surfaces near the trailing edge with negative camber on the airfoil ahead of the slot and substantial positive camber rearward of the slot. A wing-fuselage configuration incorporating the proposed airfoil has been investigated. The wing of this model has 35° of sweepback of the quarter-chord and an aspect ratio of 10.

Presently, a cruise Mach number of approximately 0.90 has been achieved with the supercritical-wing—fuselage configuration. The drag at the cruise condition is about 5 percent lower than that for comparable conventional configurations. Also, the new supercritical airfoil appears to afford a substantial improvement in high lift stability and buffeting.

INTRODUCTION

The Air Force C-5 program and the more recent considerations of a new generation of subsonic jet transports has stimulated a renewed interest in means of improving the performance of cruise airplanes at high subsonic speeds. The principal factor limiting the performance of such airplanes is the drag rise which occurs at about a Mach number of 0.8 for the current generation of jet transports. This drag rise not only limits the speed of the airplane but also reduces the lift-drag ratio at the cruise point. Both factors adversely affect airplane operating costs.

The most widely used means for delaying the drag rise is wing sweepback; however, excessive wing sweepback results in a reduction in the aerodynamic aspect ratio for a given structural panel aspect ratio, an increase in the severity of the pitch-up problem, and a reduction in the lift coefficient for landing and take-off. Because of these problems, the sweep utilized in the current generation of transports and in several recent cargo-type configurations has been limited to 35° at the quarter-chord. More recently, several U.S. aircraft companies and the British, particularly Pearcey (ref. 1), have developed refinements in essentially conventional airfoil shapes to provide moderate delays in the drag rise. These refinements have been incorporated in the several recent cargo-type configurations.

In the present paper, a drastic change in airfoil shape, which results in substantially greater delays in drag rise than those previously achieved, is discussed. This airfoil shape incorporates a slot between the lower surface and the upper surface near the trailing edge with negative camber in the airfoil ahead of the slot and substantial positive camber rearward of the slot. Because the flow over a substantial portion of this airfoil is supercritical at the cruise condition, it is referred to as a supercritical airfoil. It should be emphasized that the research on this concept is continuing on an intensive basis, and the present paper should be considered a status report rather than a final summary.

SYMBOLS

b	span
C_D	drag coefficient
C_L	lift coefficient
C_m	pitching-moment coefficient, referred to $\bar{c}$
C_p	pressure coefficient
$C_{p,sonic}$	pressure coefficient corresponding to local Mach number of 1.0
c	wing chord
$\bar{c}$	wing mean aerodynamic chord
c_d	section drag coefficient
c_m	section pitching-moment coefficient, referred to 0.25c
c_n	section normal-force coefficient
M	Mach number
t	wing thickness
y	spanwise distance

FLOW PHENOMENA

In order to illustrate the basic flow phenomena for conventional airfoils (NACA 64A-series) and the new supercritical airfoil, schematic illustrations of the flow fields and chordwise surface pressure distributions, based on wind-tunnel measurements, are presented in figure 1. The flow phenomena for the conventional airfoil are shown at a Mach number of 0.69 which is higher than that for the initiation of drag rise (M = 0.67), and those for the new supercritical airfoil are shown at a Mach number of 0.79 which is slightly lower than that for the initiation of drag rise (M = 0.80). (See fig. 2.)

When a subsonic cruise airplane approaches the speed of sound, a local region of supersonic flow develops above the wing. (See sketch in the upper left of fig. 1.) This supersonic flow is decelerated to subsonic flow through a shock wave. The shock wave produces some energy loss and thus a drag increase. More importantly, the shock wave usually causes separation of the boundary layer on a conventional airfoil. Most of the drag rise is associated with this separation. The separation is a result of the boundary layer having insufficient momentum to traverse the total pressure rise of the shock wave and the normal subcritical pressure recovery. (See the pressure distribution in the lower left of fig. 1.)

In the new supercritical airfoil, a slot between the lower and upper surfaces is placed at an intermediate point in the combined pressure rise. (See schematic drawing in upper right of fig. 1.) (The part of the airfoil ahead of the slot is referred to herein as the fore component, that behind the slot as the aft component.) With such an arrangement, the boundary layer on the upper surface of the fore component of the airfoil and the second boundary layer on the upper surface of the aft component both experience a pressure rise less than the total rise on a conventional airfoil; therefore, the tendency toward boundary-layer separation is reduced. Ideally, the airfoil is shaped to provide only the pressure rise due to the shock wave on the fore component whereas the pressure recovery that follows is concentrated on the aft component.

When boundary-layer separation is reduced or eliminated, the severe drag rise is delayed to a higher Mach number. At the higher Mach number, the drag due to shock losses increases. This drag increment is an order of magnitude less than that associated with the separation; however, for subsonic-cruise-type airplanes any drag rise is unacceptable. Therefore, the supercritical airfoil has been reshaped to reduce the drag associated with the shock losses. The energy losses in a shock wave are lessened by reducing the extent of the shock wave and diminishing the Mach number ahead of the wave. Both of these effects are accomplished in the supercritical airfoil by reducing the curvature and slope of the upper surface of the fore component. With such a reshaping, the supersonic region is as shown in the sketch in the upper right of figure 1. The extent of this region reaches a maximum and then decreases ahead of the shock wave. In contrast, for a conventional airfoil shape the supersonic region continually expands to the shock as shown in the sketch in upper left of figure 1. Also, as indicated by the pressure distributions, the Mach number ahead of the shock wave on the supercritical airfoil is substantially less than that on a conventional airfoil.

With the reduced curvature of the upper surface, the lower surface of the wing must have additional curvature for a wing with a given thickness ratio. For the fore component of the new supercritical airfoil, the camber is effectively negative. Obviously, an airfoil with negative camber and low angle of attack produces very little lift; the required lift for cruise is achieved by incorporating substantial positive camber into the aft component of the airfoil.

Because of the increase in Mach number provided by the airfoil and the increased curvature of the lower surface, supercritical flow and a shock wave develop on the lower surface of the fore component at the probable cruise condition (fig. 1). In addition, a large pressure rise occurs on the lower surface of the airfoil at the point of reversal of the camber line. The addition of the pressure rise of the shock wave to the pressure rise associated with camber reversal gives a total pressure rise approximately equal to that on the upper surface of a conventional airfoil at supercritical conditions. Without the slot, this pressure rise would undoubtedly cause boundary-layer separation. However, the presence of the slot greatly reduces the tendency toward such separation in an action similar to that on the upper surface. The boundary layer on the fore component experiences only part of the total rise before being accelerated in the slot. The rest of the pressure rise occurs near the leading edge of the aft component where the boundary layer is very stable and can traverse the rise. Again, as for the upper surface, the lower surface should be shaped so that the pressure rise on the fore component is limited to that associated with the shock wave whereas the rest of the rise is concentrated on the aft component. Thus, the slot is necessary to control boundary-layer separation on the lower surface as well as on the upper surface.

A more complete discussion of the flow phenomena associated with the proposed supercritical airfoil is presented in reference 2.

TWO-DIMENSIONAL INVESTIGATION

In order to evaluate and develop the supercritical airfoil shape, a two-dimensional airfoil model was investigated in the Langley 8-foot transonic pressure tunnel (ref. 2). The model completely spanned the tunnel with the two solid side walls of the tunnel acting as large end plates. The normal force and pitching moment of the airfoil were determined by pressure distributions; drag was determined from wake survey measurements. The airfoil utilized had a thickness of $13\frac{1}{2}$ percent chord. As a basis for reference, an NACA 64A-series airfoil which is representative of the airfoil shapes on current jet airplanes was also investigated.

Variations of drag coefficient with Mach number at a normal-force coefficient of 0.65 for the supercritical airfoil and for the NACA 64A-series airfoil are shown in figure 2. The 64A-series airfoil experienced a drag rise at about a Mach number of 0.67. The more recent airfoil shapes mentioned in the introduction would probably experience a similar drag rise at a Mach number of 0.70. The supercritical airfoil has a gradual increase in drag to a Mach number of about 0.78. This gradual rise is associated with small amounts of shock loss. Between $M = 0.78$ and 0.79 the drag decreases somewhat, and then it increases sharply. This abrupt increase in drag is associated with a movement of the shock wave to a point rearward of the slot exit. For such a condition, the entire pressure rise of the shock plus the normal pressure recovery occur on the aft component with a resulting flow separation on the upper surface. Thus, the effectiveness of the new airfoil shape in delaying drag rise is limited.

The dip in the drag variation between $M = 0.78$ and 0.79 is real. The schlieren photographs, wake surveys, and pressure distributions all indicate that the shock wave disappears. The exact reasons for this complete disappearance of the shock wave are not fully understood. A discussion of a possible reason is given in reference 2. However, from a practical standpoint, the most important characteristic of the airfoil is the relatively low drag increments due to shock losses for Mach numbers up to 0.79.

The variations of pitching-moment coefficient with Mach number at a normal-force coefficient of 0.65 for the supercritical airfoil and for the reference 64A-series airfoil are presented in figure 3. The supercritical airfoil has a large negative pitching moment. This moment is the result of the large load on the aft component. (See pressure distribution in lower right of fig. 1.) For an unswept wing, the drag associated with trimming such a moment would probably be prohibitive; however, for a sweptback wing, this negative pitching moment is not necessarily a problem as is discussed in the section "Results and Discussion."

Additional aerodynamic characteristics obtained from the two-dimensional investigation are presented in reference 2.

THREE-DIMENSIONAL INVESTIGATION

Configuration

In order to determine whether the delay in drag rise achieved for the relatively simple two-dimensional situation can be attained for the much more complex three-dimensional case, an investigation of a swept-wing—fuselage model incorporating the supercritical airfoil was made. The wing-fuselage configuration utilized for the three-dimensional investigation is shown in figures 4 and 5. The wing of the model has 35° of sweep at the quarter-chord; this sweep angle is the same as that for most current jet airplanes and several recent cargo-type configurations. The wing also has an aspect ratio of 10, a value significantly higher than the wing aspect ratio for current transports. However, the thickness ratios for the various sections of the wings are greater than those currently used; therefore, the wing bending structural problem is not significantly different from that for current designs. The use of a higher aspect ratio and greater section thickness ratios needs some explanation. An analysis of the characteristics of the new airfoil suggested that the maximum overall performance to be gained through the use of the new airfoil could be achieved if only part of the effectiveness of the shape is utilized to increase speed whereas the rest of the effectiveness is utilized to increase the cruise lift-drag ratio.

The wing was investigated with 4° of twist. To simplify model construction, the actual model had no twist. The twist was effectively achieved by rotating the flow in the wind tunnel into two circulation patterns symmetrically displaced with respect to the vertical center plane of the tunnel.

The shapes of the airfoils at various stations along the semispan of the wing are shown in figure 6. These airfoil shapes were not arrived at by mathematical calculations. The flow fields are highly nonlinear. The maximum Mach number on the upper surface was about 1.6 and the minimum Mach number on the lower surface was about 0.6. Further, the favorable influence of the supercritical airfoil on drag rise superimposed on the favorable effect of sweepback results in a probable cruise Mach number approaching the speed of sound. At these higher subsonic Mach numbers, the lateral disturbances produced by the various elements of the configuration expand rapidly so that a strong mutual interference exists between the flow fields about the several elements. No available theory can predict the required surface shapes for such three-dimensional, nonlinear conditions. Instead, on the basis of pressure distributions, surface oil films, and schlieren photographs, deviations from the desired flow fields were determined experimentally for the initial configuration. Then, on the basis of these measurements and the fundamental laws governing mixed flow, the initial shape was modified progressively to arrive at the final desired flow fields.

As shown in figure 4, the slot does not extend along the entire span of the wing. The load on the tip section is relatively low compared with that on the inboard sections; the thickness ratio of the tip is also relatively small. Therefore, the slot was believed not to be needed to control the flow on this less critical region. The surface oil film measurements indicate that the flow moves smoothly over this tip region.

The fuselage of the configuration was specially shaped and a thick glove was added to the forward region of the inboard sections of the wing to provide a longitudinal area development for the configuration approaching that for an ideal transonic body. The glove was necessary in order to allow satisfactory contours of the fuselage.

Results and Discussion

The variation of drag coefficient with Mach number at a lift coefficient of 0.5 for the configuration incorporating the supercritical airfoil is shown by the solid line in figure 7. For comparison, the average of similar results obtained for two recent cargo-type configurations (hereinafter referred to as reference) having the same sweep angle as the present model - that is, 35° of the quarter-chord - are presented as the dashed line labeled "recent technology." The investigations of the present and reference configurations were made in the Langley 8-foot transonic pressure tunnel with the same balance and support sting. The ratio of wing span (approximately 5 ft) to tunnel width was the same. The Reynolds number for the present investigation was approximately one-half that for the investigations of the reference configurations.

For the reference configurations, boundary-layer transition strips were placed near the leading edge on the upper surface and lower surface of the wing and on the fuselage. For the supercritical configuration, similar strips were placed on the upper surface of the wing and on the fuselage. However, the strip on the lower surface was moved rearward to approximately the 50-percent-chord station to provide a ratio of boundary-layer thickness to slot height in the slot, which approximates that probably present in the slot on a full-scale airplane. Such a procedure for simulating a full-scale boundary-layer thickness is described in paper no. 3 by Loving. Boundary-layer strips were also placed on the upper surface of the aft component of the airfoil.

The drag results for the several configurations have been adjusted to provide results for the same relative fuselage volume to wing area and a closed fuselage aft end. The drag results obtained for the supercritical configuration have been adjusted upward to provide the drag level which would have been associated with a transition-strip location similar to that for the reference configurations. All results have been adjusted, on the basis of the usual variation of turbulent skin friction with Reynolds number, to a condition approximating that for an airplane of the C-5 size operating at an altitude of 35 000 feet. Such an adjustment provides a more realistic comparison of the results for the supercritical configuration and those obtained for the reference configuration. The slot, aft component struts support, glove, and the greater induced velocities on the surface of the supercritical configuration all increase the skin friction compared with that of the reference configurations. Thus, a comparison of the drag results at wind-tunnel Reynolds numbers would show a penalty for the supercritical configuration substantially greater than that for full-scale Reynolds numbers.

The curve for the reference configurations shows an abrupt drag rise at a Mach number slightly higher than 0.82. The supercritical configuration experienced a similar rise at a Mach number slightly higher than 0.9; thus, the drag rise has been delayed approximately 0.08 Mach number or 10 percent. The drag at a Mach number of 0.9 for the supercritical configuration is approximately 5 percent less than that for the reference configurations at a Mach number of 0.82. An analysis of the several differences between the supercritical configuration and the reference configurations indicates that the increased aspect ratio should result in a 9-percent reduction in drag and that the added skin friction should increase the drag approximately 4 percent. The delay in drag rise provided by the supercritical configuration for a substantial lift-coefficient range above and below 0.50 is approximately equal to that shown in figure 7; however, at very low lift coefficients, the delay is reduced because of separation on the lower surface of the supercritical configuration.

The pressure distributions measured at a Mach number of 0.9 for a lift coefficient of 0.50 are shown in figure 8. These pressure distributions indicate no severe wave drag problems. The surface oil films for the same condition indicate no significant regions of separation. A small bubble of separation occurs on the outboard region of the lower surface at the entrance to the slot just aft of the negative pressure peaks noted in the pressure distributions. Further refinements in the shape in this region should eliminate the pressure peak and the associated separation bubble.

The pressure distributions for a Mach number of 0.92 at a lift coefficient of 0.48, as presented in figure 8, indicate that the drag rise present at this Mach number is caused by a sudden rearward shift of the shock wave on the outboard region of the upper surface to a position near the slot. The surface oil films indicate that this shock caused separation on the aft component and on a small region of the fore component. This separation pushed the shock wave forward in this region, as indicated by the pressure distributions. A discussion of the effect of separation on shock position is presented in paper no. 3 by Loving. The pressure distributions shown in figure 8 and the surface oil films for the same condition indicate no separation and insignificant shock losses on the entire inboard region of the configuration at $M = 0.92$. Similar detailed flow measurements indicate no severe problems in this inboard region until a Mach number of 0.95 is exceeded. Thus, it appears that, to obtain further delays in the drag rise Mach number, the rapid rearward movement of the shock wave on the outboard region of the wing must be retarded. A study of several means for accomplishing this action is being planned.

To date, no investigations of the effects of adding nacelles to the configuration have been made but such an investigation is planned. During this investigation, a detailed analysis of the flow phenomena associated with the favorable pylon-nacelle-wing interference described by Patterson in paper no. 18 will be made, with the intent, of course, of increasing this favorable interference.

A limited comparison of the trim, stability, and buffet characteristics for the supercritical configuration with those based on the reference configurations (labeled "recent technology") are shown in figure 9. The results shown for the supercritical configuration are for a Mach number of 0.85 which is 0.05 less than the probable cruise Mach number. The reference results are presented for a corresponding Mach number of 0.77. At a lift coefficient of 0.5, the results for the reference configurations show a pitching moment of approximately -0.05. Such a negative pitching moment causes no severe trim problem. The supercritical configuration had a near zero pitching moment at the same lift coefficient. Thus, in contrast to the very large negative pitching moment for the two-dimensional supercritical airfoil, as discussed in the section "Two-Dimensional Investigation," the swept wing with such an airfoil has a less negative pitching moment than wings with conventional airfoils. The glove added to the leading edge of the inboard sections and the wing twist required to obtain the desired span load distribution at the cruise condition provided a positive pitching-moment increment which offset the negative pitching moments of the sections.

The results presented in figure 9 indicate that the supercritical configuration experienced an increase in stability beyond a lift coefficient of approximately 0.6. No abrupt decrease in stability was observed to a lift coefficient of 0.95 at which moderate buffeting occurred. Because of the inadequacy of the stiffness of the support system during the investigation of the supercritical configuration, no attempt was made to obtain data after buffeting occurred. The results for the reference configurations show a decrease in stability at $C_L \approx 0.7$.

An indication of the possible influence of the new airfoil shape on buffet characteristics was also obtained during the investigation. It is realized that a quantitative indication of buffeting can be obtained only in flight or with a dynamically similar model in a wind tunnel. The models of the supercritical configuration and the reference configurations are not dynamically similar to airplanes. However, a qualitative comparison of the buffet characteristics for the supercritical configuration and for the reference configurations is provided by model buffeting or shake. For the reference configurations initial model buffeting occurred at $C_L \approx 0.7$, the lift coefficient at which the abrupt decrease in stability occurred. (See fig. 9.) The model of the supercritical configuration buffeted at a lift coefficient of about 0.95, a value one-third higher than that for the reference configurations. These limited stability and buffet results suggest that the flow through the slot and the shape of the supercritical airfoil probably provide a strong favorable effect on boundary-layer separation at high lift coefficients as well as the design condition.

Thus far no results have been obtained which define the landing and takeoff characteristics at low speeds for the configuration with the supercritical airfoil. However, as shown in figure 6, the present model has very large leading-edge radii (0.027c). The favorable influence of such radii on the low-speed, high-lift characteristics should more than offset any adverse effect of the negative camber of the fore component. Thus, there appears to be no obvious reason for the characteristics at low speeds being any worse than those for configurations with conventional airfoils. The aft component of the supercritical airfoil can probably be incorporated into the low-speed landing-flap system and, thus, should not materially increase the complexity of an already complex airplane.

The determination of the influence of the new airfoil on wing weight will require a very comprehensive analysis. However, one factor controlling this weight is discussed here briefly. At the cruise condition, the aft component produces approximately 40 percent of the lift of the wing. However, the structure of the airplane configuration is usually designed on the basis of the higher maneuver lifts. When the angle of attack is increased to produce these higher lifts, the load on the aft component remains approximately constant and the fore component produces the additional lift. Therefore, the proportion of the load on the aft component at these conditions is substantially less than that at the cruise condition. Thus, it might be expected that the structural weight penalty associated with the loads on the aft component would not be as great as indicated by the load distributions obtained at the cruise lift coefficient.

CONCLUDING REMARKS

Presently, with a swept-wing configuration incorporating the proposed supercritical airfoil, a subsonic cruise Mach number of 0.90 has been achieved. This Mach number is approximately 10 percent higher than that for the most recent comparable configurations with essentially conventional airfoils. The drag at near the cruise condition is about 5 percent lower than that for the comparable conventional configurations. Also, it appears that the supercritical airfoil affords a significant improvement in high lift stability and buffeting.

Further research may reveal insurmountable problems. On the other hand, it is likely that the research will indicate further advantages for the new airfoil shape. For the present, the results presented indicate that the proposed concept has interesting practical promise.

REFERENCES

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2. Whitcomb, Richard T.; and Clark, Larry R.: An Airfoil Shape for Efficient Flight at Supercritical Mach Numbers. NASA TM X-1109, 1965.

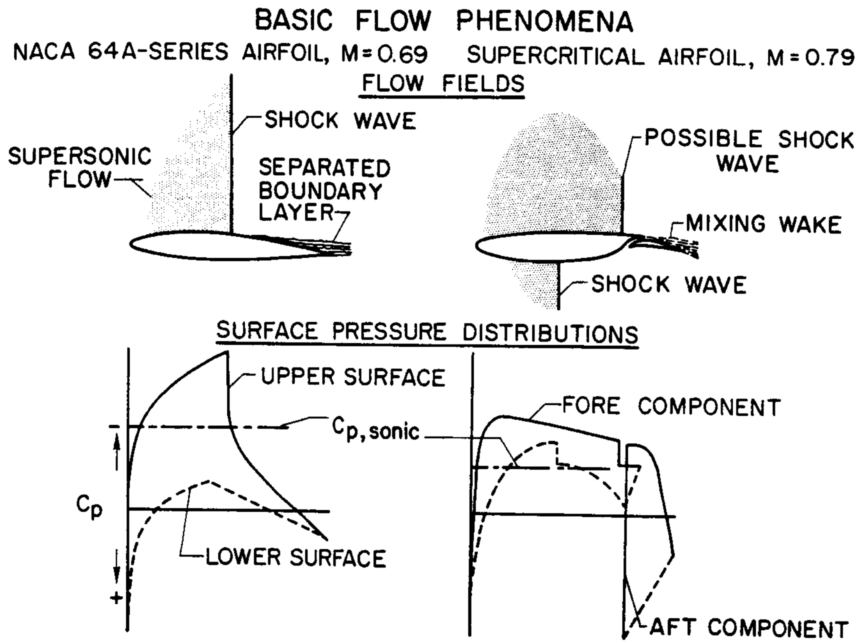

Figure 1

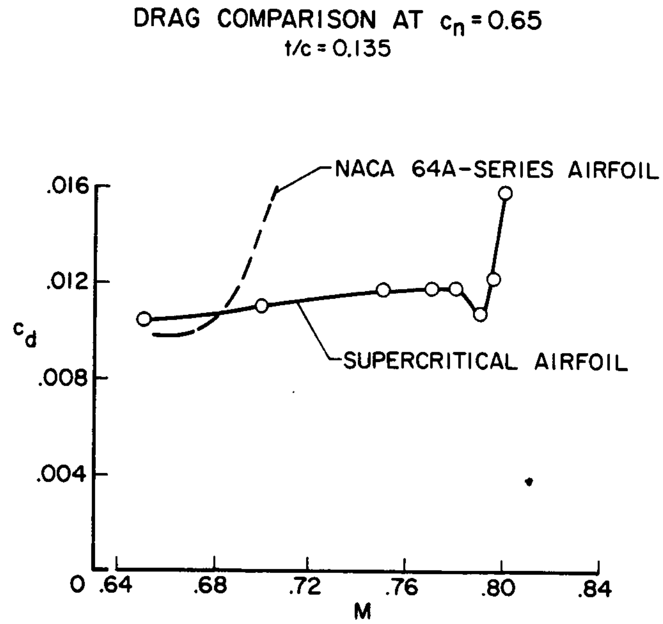

Figure 2

PITCH COMPARISON AT $c_n = 0.65$

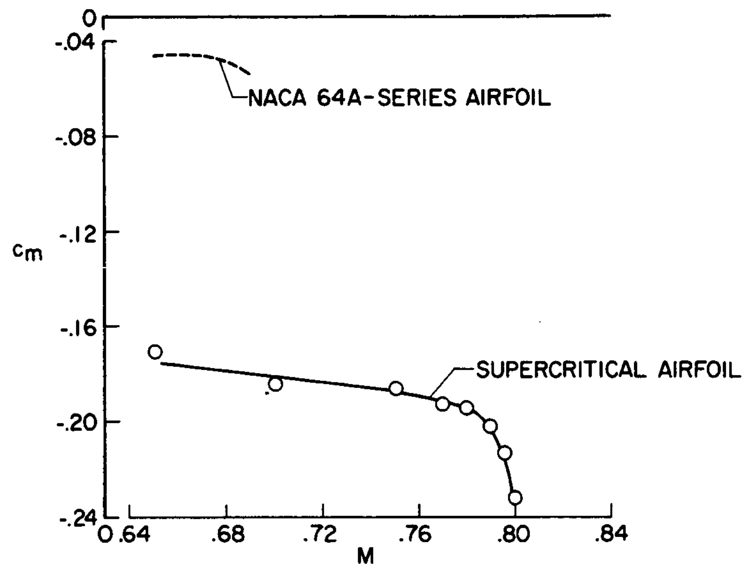

Figure 3

PLAN VIEW OF CONFIGURATION INCORPORATING SUPERCRITICAL AIRFOIL

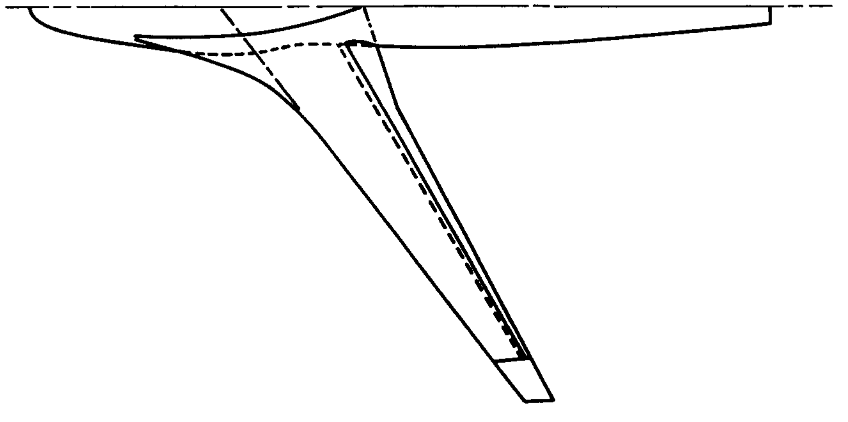

Figure 4

CONFIGURATION INCORPORATING SUPERCRITICAL AIRFOIL

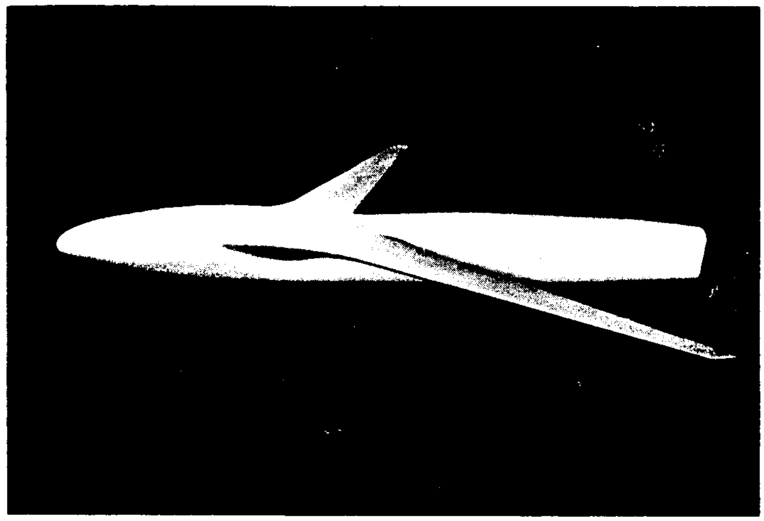

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Figure 5

AIRFOIL SHAPES FOR SUPERCRITICAL WING

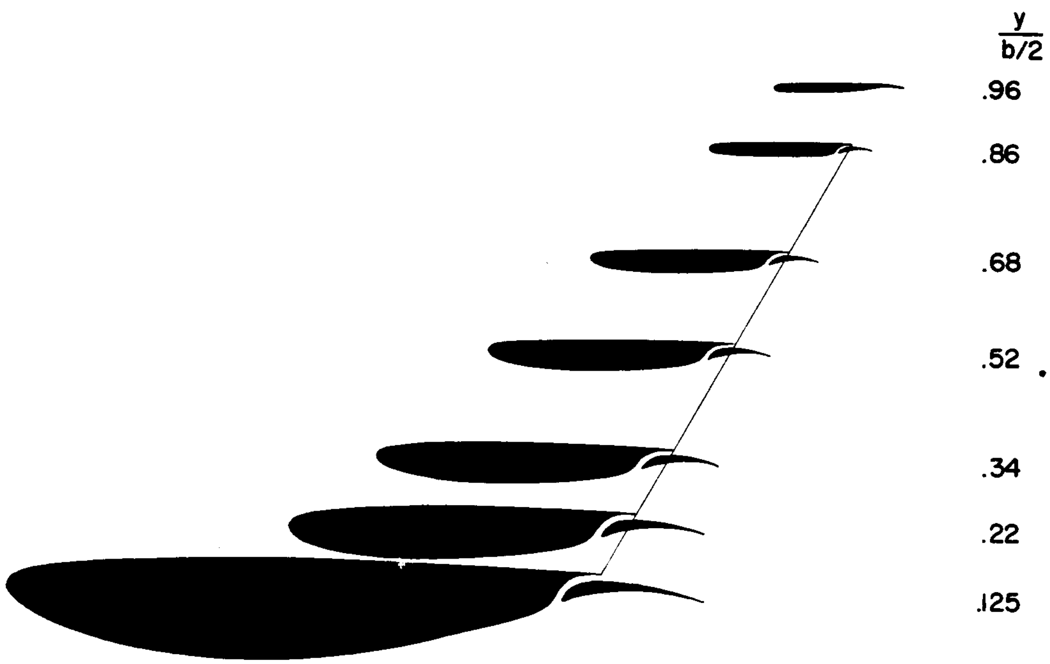

Figure 6

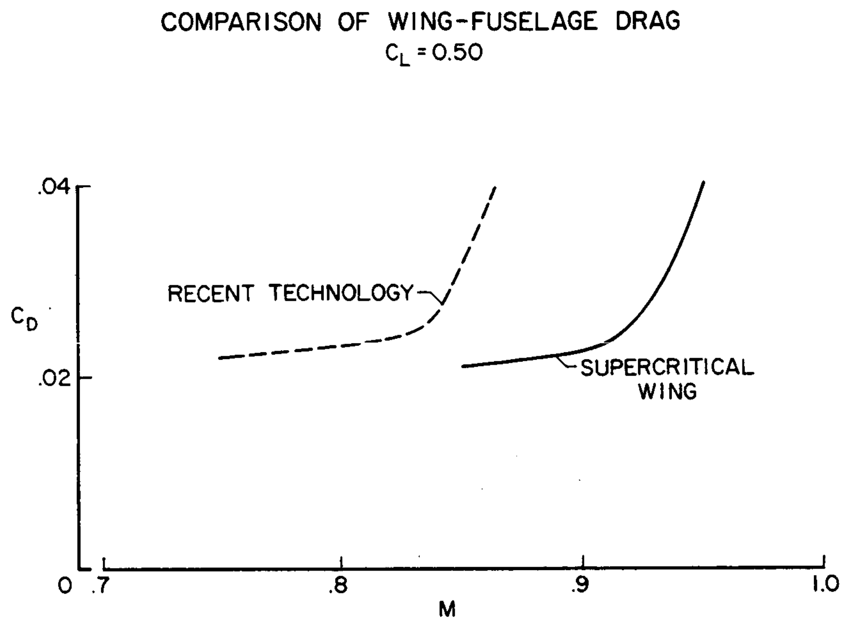

Figure 7

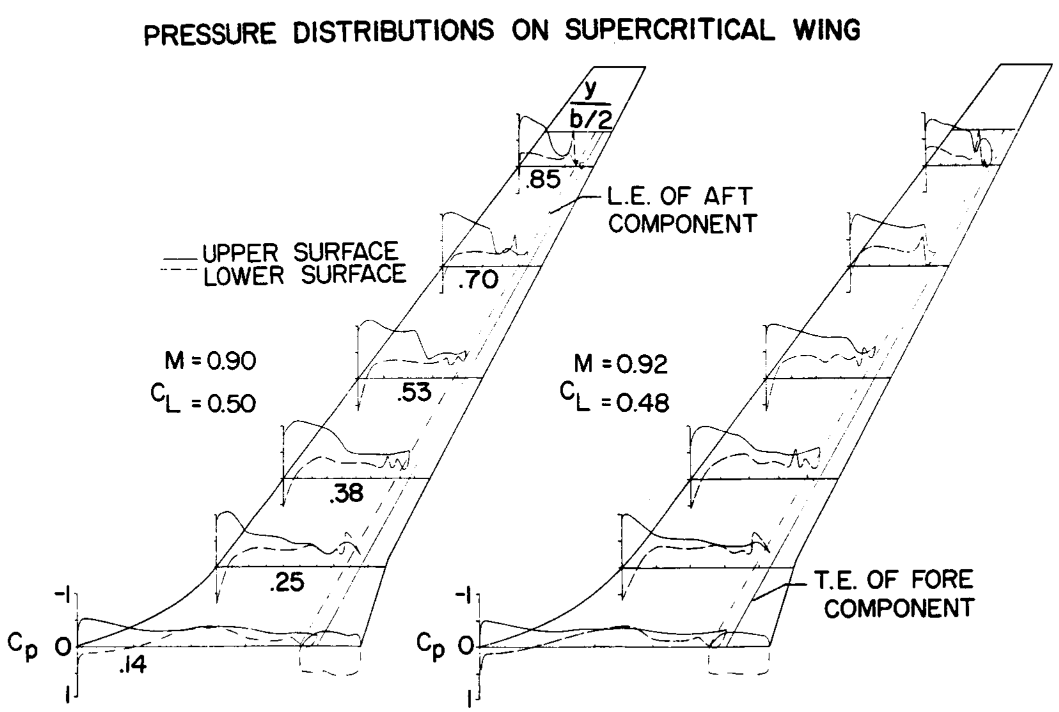

Figure 8

COMPARISON OF WING-FUSELAGE PITCHING MOMENTS

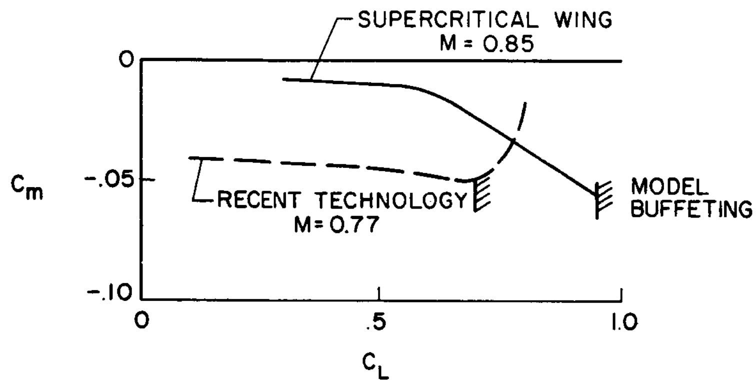

Figure 9