ADVANCED TRANSONIC AERODYNAMIC TECHNOLOGY

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SUMMARY

The primary discussion is of NASA supercritical airfoils and their applications to wings for various types of aircraft. The various wings discussed have been designed for a subsonic jet transport with increased speed, a variable sweep fighter with greater transonic maneuverability, a high subsonic speed STOL jet transport with improved low speed characteristics, and a subsonic jet transport with substantially improved aerodynamic efficiency. Results of wind tunnel and flight demonstration investigations are described. Also discussed are refinements of the transonic area rule concept and methods for reducing the aerodynamic interference between engine nacelles and wings at high subsonic speeds.

INTRODUCTION

It is generally recognized that the transonic speed range is that in which the flow about an aerodynamic configuration is an interacting mixture of subsonic and supersonic fields. The Mach number for the onset of such conditions is called the critical Mach number, thus transonic flow at subsonic freestream Mach numbers is called supercritical flow. Most high performance aircraft operate at least part time at supercritical or transonic conditions. Therefore, this speed regime is of great practical interest. Further, because of the mixture of subsonic and supersonic flow fields both the theoretical and experimental research in this area is extremely complex. Because of the practical interest and the complexity, extensive theoretical and experimental research is being conducted in this area. This research has led to a number of significant advances in recent years. The theoretical work in this area is covered by other papers of this conference. In this paper some of the experimental research will be described. Because of the prescribed brevity of the paper only that work with which the author has been directly involved will be discussed. Even this discussion is, of necessity, very superficial.

SYMBOLS

c	airfoil chord
c_d	section drag coefficient

C_D	airplane drag coefficient
C_L	airplane lift coefficient
C_p	pressure coefficient
c_n	section normal-force coefficient
M	Mach number
t	airfoil maximum thickness

NASA SUPERCRITICAL AIRFOILS

Description

The well-known flow problem for conventional airfoils at high subsonic speeds is illustrated at the top of figure 1. A local region of supersonic or supercritical flow develops above the upper surface of a lifting airfoil which terminates in a strong shock wave. The wave itself causes some increase in drag, but usually the principal effect is separation of the boundary layer with a significant increase in drag, stability problems, and buffet. For the NASA supercritical airfoils, as shown at the bottom of figure 1, the curvature of the middle region of the upper surface is substantially reduced with a resulting decrease in the strength and extent of the shock wave. The drag associated with the wave is reduced and, more importantly, the onset of separation is substantially delayed. The lift lost by reducing the curvature of the upper surface is regained by substantial camber of the rear portion of the airfoils.

The airfoils also incorporate other features which are important to the total effectiveness of the new shape. The middle region of the lower surface is designed to maintain subcritical flow for all operating conditions of the airfoils, because the pressure rise associated with a shock wave superimposed on the pressure rise caused by the cusp would cause separation of the lower-surface boundary layer. To minimize the surface curvatures and thus the induced velocities on the middle regions of both the upper and lower surfaces, the leading edge is made substantially larger than for previous airfoils. It is more than twice that for a 6-series airfoil of the same thickness-to-chord ratio.

The rear portion of the upper surface is designed to produce a constant or decreasing pressure behind the shock wave for the design condition. This feature stabilizes the boundary layer behind the shock before it enters the subsonic pressure recovery. In particular, it substantially delays the final detachment of the boundary-layer bubble present under the strong shock for high-lift conditions. Results to be presented later will define this effect more explicitly. The pressure distribution on the aft portion of the lower surface is designed by the Stratford criteria to obtain the largest increase in lift by the cusp without incurring boundary-layer separation in the cusp. This involves a rapid initial increase in pressure followed by a more gradual increase. At the trailing edge the slope of the lower surface is made approximately equal to that of the upper surface to reduce to a minimum the required pressure recovery at the upper-surface trailing edge.

At Mach numbers or lift coefficients less than the design conditions, the shock wave is farther forward with an increase in velocity aft of the shock to a second velocity peak in the vicinity of the three-quarter chord. This peak must be carefully controlled to prevent the development of a second shock with associated separation on the extreme rearward portion of the airfoils. At Mach numbers higher than the design value, the shock wave moves rearward and becomes stronger. Also, the pressure plateau disappears. As a result, the boundary layer usually separates aft of the shock. A more complete description of the aerodynamic flow on the NASA supercritical airfoils at and off the design condition is presented in reference 1.

Two-Dimensional Results

A comparison of the drag variation with Mach number at a normal-force coefficient of 0.7 for a 10-percent thick conventional airfoil (NACA 64A-410) and two 10-percent thick versions of the NASA supercritical airfoils is shown in figure 2. The early supercritical airfoil for which results are shown is similar to that used for all applications up to 1973. The abrupt drag rise for this airfoil is more than 0.1 Mach number later than that for the 6-series airfoil. This early supercritical airfoil experienced a drag creep at Mach numbers below the abrupt drag rise. This drag is associated with relatively weak shock waves above the upper surface at these speeds.

Much of the recent work at Langley has been devoted to the elimination of this undesirable drag creep, and the solid curve of figure 2 shows an example of the results of these efforts. Refinements to the airfoils were involved primarily with changes which resulted in a more favorable flow over the forward region of the upper surface and the elimination of the region of flow overexpansion near the three-quarter chord location on the upper surface. A slight loss in force-break or drag-divergence Mach number is noted (about 0.01) as a result of slightly increased wave losses at the higher Mach numbers, but this compromise is felt to be of little consequence relative to the gains achieved in eliminating drag creep. It should be noted that, unlike the early work, the shaping changes used in the design of the recent airfoils were guided in part by the use of the recently developed analytical program of reference 2 to achieve desired pressure distributions for the various cases.

In figure 3 the Mach number for the onset of severe separation, that is, for buffet or abrupt drag rise, is plotted against normal-force coefficient for the same airfoils as in the previous figure. The results indicate that not only does the supercritical airfoil delay drag rise at near cruise lift coefficients but it also substantially increases both the Mach number and lift coefficient at the characteristic high-lift corner of the curve. This effect, which results primarily from the stabilization of the bubble under the shock wave as discussed earlier, is particularly important for improving maneuverability.

Recent airplane designs incorporate airfoils with somewhat higher drag rise Mach numbers than for the NACA 6-series shown here. However, it has been difficult to acquire two-dimensional data for such airfoils. Results obtained with a C-5A airplane model in the Langley Research Center 8-foot tunnel indicate that one of these new shapes, the Pearcey peaky airfoil, delays the drag-rise Mach number 0.02 or 0.03 compared with the NACA 6-series airfoils but at a loss in the maximum lift.

The aft loading (fig. 1) associated with the new shape results, of course, in more negative pitching moments.

Supercritical technology can also be used to substantially increase the thickness ratios of an airfoil without an associated reduction in the Mach number for separation onset. Obviously, the increased thickness allows a weight reduction or an increase in aspect ratio and provides added volume for fuel or other required equipment in the wing. Figure 4 shows a 17-percent thick airfoil designed by W. E. Palmer of the Columbus Division of the Rockwell International Corporation. A more detailed description of this airfoil is presented in reference 3.

APPLICATIONS OF SUPERCRITICAL AIRFOILS

Three-Dimensional Wing Considerations

Explicit theoretical methods for designing three-dimensional swept-wing configurations for supercritical flight conditions are not as fully developed as those for two-dimensional configurations. However, some rational qualitative approaches have been developed which will be discussed briefly.

For wings of reasonably high aspect ratio, the airfoil sections of the midsemispan and outboard regions can be the same as those of the two-dimensional airfoils. For the supercritical wing developed for the F-8 flight demonstration to be described later and shown in figure 5 such an agreement holds even for sections on the outboard part of the nontrapezoidal region of the wing. The section near the wing-fuselage juncture is substantially different in detail from the two-dimensional section. However, even here some aft camber provided the most satisfactory results.

Substantial wing twist is usually required for the best overall performance of supercritical swept wings, as for previous swept wings intended for high-speed flight. Experiments at the Langley Research Center and in industry have indicated that for both previous and supercritical swept wings a twist significantly greater than that which theoretically provides an elliptical load distribution provides the best overall design. This large amount of twist substantially reduces or eliminates the trim penalty associated with the greater negative pitching moment for the supercritical airfoil for a sweptback wing.

The planform as shown in figure 5 is an important part of obtaining a high drag-rise Mach number as well as a practical structure for a swept wing. The rearward extension of the root section allows for the attachment of landing gear in a transport application of such a wing. The glove extending forward is an attempt to provide the same drag-rise Mach number for the root sections as for the outboard regions of the wing. Experiments and theory have indicated that at supercritical speeds the isobars on any sweptback wing move rearward near the root sooner and more rapidly than outboard, with a resulting premature drag rise for this region. The forward root extension turns the isobars forward for subcritical conditions, so that at supercritical design conditions the sweeps of the isobars of the inboard region more nearly match those of the outboard region. The wing shown in figure 5 is described in more detail in reference 4.

Flight Demonstration Program

Because of the drastically different nature of the flow over the supercritical airfoils there was considerable concern as to how the new shape would operate in actual flight. Therefore, the several U. S. government agencies responsible for the development of aircraft, that is NASA, the Air Force, and the Navy, undertook a coordinated, three-part flight demonstration program. The program was to evaluate the application of the new airfoils to a high speed, long-range transport wing configuration, a thick wing, and a variable-sweep fighter wing. In each case existing military aircraft were used as test beds. However, in none of the cases was it intended the test wing would be applied to production versions of these aircraft.

The transport wing configuration was flown on a Navy F-8 fighter (fig. 6). The wing was designed for cruise at very close to the speed of sound ($M \approx 0.98$). This program was sponsored by NASA. The wing structure was designed and fabricated by Los Angeles Division of the Rockwell International Company and the flight tests were conducted at the NASA Dryden Flight Research Center. Results from this program are presented in reference 3.

The thick wing was flown on a Navy T-2C trainer. A comparison of aircraft with and without the thick section is shown in figure 7. This program was sponsored by the Navy and NASA. The configuration and structural design, fabrication, and flight tests were conducted by the Columbus Division of the Rockwell International Company. Results from this program are presented in reference 3.

The variable sweep fighter wing was flown on an Air Force F-111 (fig. 8). The wing was designed to achieve substantially improved maneuverability at high subsonic speed and a higher cruise speed. This program, called TACT, was sponsored by the Air Force and NASA. The wing structure was designed and fabricated by the Fort Worth Division of the General Dynamics Company and the flight tests were conducted at the NASA Dryden Flight Research Center. The initial wind tunnel results of this program are presented in reference 5.

The results from all three flight programs verified the wind tunnel results. The performance gains predicted were achieved and no off design problems were encountered.

Recent Applications

The first U. S. pre-production prototype airplane configurations to incorporate NASA supercritical airfoils are the Air Force advance medium STOL transport (AMST) configurations designed by the McDonnell Douglas Company (YC-15) and the Boeing Company (YC-14). The Douglas configuration is shown in figure 9. The advantage of this airfoil in delaying the onset of the adverse supercritical flow effects has been exploited in these aircraft by eliminating wing sweep. This change allows higher useable lift coefficient for landing and take off with a resulting improvement in the performance for these conditions.

In the initial effort of applying NASA supercritical airfoils to transport aircraft it was assumed that the airfoil should be exploited through an increase in the speed, since this had been the traditional area of advance for such aircraft. The work on the wing demonstrated on the F-8 took this direction. With the recent dramatic increase in the price of fuel the airlines are now more interested in fuel economy rather than speed. Therefore, the more recent research effort at the Langley Research Center has been directed toward using these airfoils to achieve high lift-to-drag ratios. This research is summarized on figure 10. As has already been mentioned the airfoils allow an increased thickness-to-chord ratio for a given drag rise Mach number. This allows a greater span with the same structural weight which, of course, results in lower induced drag. With the higher span the design lift coefficient must be increased. Also, as for the AMST configurations described previously, the use of this airfoil allows a reduction of wing sweep with a resulting improvement of the landing and take off characteristics. In this case the improvement is exploited by a reduction in wing area and thus weight. One of the models used in this investigation is shown in figure 10. The wind tunnel results indicate that for a given wing weight the lift-to-drag ratio can be increased by 18 percent at the cruise Mach numbers of current transports.

AREA RULE REFINEMENTS

The area rule, developed in the 1950's, is a concept which relates the shock wave drag of airplane configurations at transonic and supersonic speeds to the longitudinal development of the cross-sectional area of the total configuration. On the basis of this concept the minimum wave drag for an airplane configuration at supersonic speeds is achieved when the longitudinal development of cross-sectional area is the same as that for a body of revolution with minimum supersonic wave drag. The application of this concept usually results in an indented fuselage. This idea has been exploited primarily in military aircraft. Most present subsonic commercial transport aircraft do not fly at sufficiently high speeds to justify the use of this concept. However, the application of the NASA supercritical airfoil allows speeds of such transports to be such that the area rule can be applied to advantage. Following the wind tunnel development of the transport supercritical wing demonstrated on the F-8 considerable wind tunnel research was carried out on a transport configuration incorporating not only this wing but also fuselage modification based on the area rule. The configuration was intended for efficient cruise flight near the speed of sound ($M \approx 0.98$). The results of this research are presented in reference 6. During this research several improvements of the area rule concept were developed.

First, a body of revolution with an increased drag rise Mach number was developed using the same approach as that for the NASA supercritical airfoils. This body was intended to provide the basis for the optimum longitudinal development of cross-sectional area for an airplane intended for flight just below the speed of sound rather than supersonic speeds. The streamwise distribution of cross-sectional area for this body of revolution is shown in figure 11. This distribution is substantially different than that for a body with minimum wave drag at supersonic speeds. It has a nose with substantial bluntness. Also, the curvature of the distribution near the maximum area is substantially less than for the minimum supersonic wave drag body of the same fineness ratio.

The area rule is essentially a linear theory concept for zero lift. During the research on the near sonic transport configuration it was found that to achieve the most satisfactory drag characteristics at lifting conditions the fuselage shape had to be modified from that defined by the simple application of the area rule as previously described to account for the nonlinearity of the flow at such conditions. For lifting conditions at near sonic speeds there is a substantial local region of supercritical flow above the wing surface which results in local expansions of the stream tube areas. In the basic considerations of the area rule concept this expansion is equivalent to an increase in the physical thickness of the wing. To compensate for this effect the fuselage indentation required to eliminate the far field effects of the wing must be increased. The corrections in cross-sectional areas required for the transport investigated are shown at the bottom of figure 11 and are designated B. The distribution used to design the total configuration is the optimum zero lift distribution described earlier with the correction area B subtracted. The fuselage indentation based on this corrected area distribution resulted in a significant (.02) delay in the drag rise Mach number compared with that for the indentation based on the zero lift distribution.

The drag rise characteristics for the transport configuration incorporating both the supercritical wing and a fuselage shape based on the refined area rule is shown as a solid line in figure 12. The cruise Mach number is approximately 18 percent higher than that for the current wide body transports. Following the wind tunnel development of this configuration three aircraft companies under contract to NASA designed possible transport configurations based on such an arrangement. One of the designs is shown in figure 13.

WING AND ENGINE NACELLE INTERFERENCE

The initial designs of most high performance aircraft configurations with externally mounted engines have resulted in an adverse aerodynamic interference between the flows around the wing, engine nacelles, and pylons at transonic speeds. This interference results from the super-position of the induced flows of the several components. Considerable research has been conducted to reduce these adverse interferences to acceptable levels.

An extreme example of such interference was encountered during a recent wind tunnel investigation of the application of a supercritical wing to an executive or business jet. The configuration is shown in figure 14. The forward portion of the rear mounted engine extends well forward over the upper surface of the wing. Because of the curvatures of the various components a converging and then diverging channel was present between the components. As a result a high supersonic local Mach number developed in this region at the intended cruise Mach number. Wind tunnel research has indicated that the most straight forward method for greatly reducing such interference is to move the engine nacelle rearward. However, because of a balance problem for this airplane the engine could not be moved rearward. For this configuration the shapes of the upper surface of the wing and the pylons were drastically modified to provide an approximately uniform cross-sectional area channel between the components.

Results of the modifications are shown in figure 15. The configuration without the engines added is shown by the short dash line. With the initial configuration of the nacelles and pylons the drag at the intended cruise Mach number of 0.80 was increased by approximately 0.0040. The configuration was completely unacceptable. With the reshaping of the wing and pylons the drag increment is approximately 0.0010 at the cruise condition, which is about as low as can be achieved with the severe practical constraints imposed on the arrangement.

For engines mounted forward under the wing, as for many jet transports, similar interference problems can be present. They also can be greatly reduced by reshaping the configuration.

CONCLUDING REMARKS

Application of NASA supercritical airfoils can provide substantial improvements in the speed, efficiency, maneuverability, and landing and take off characteristics of aircraft intended to operate at transonic speeds. Further, refinements in the area rule concept can be used to achieve efficient cruise at very close to the speed of sound ($M \approx 0.98$). Also the proper shaping of the wing and pylon can greatly reduce the adverse aerodynamic interference which can be present between the wing engine pylon arrangement at transonic speeds.

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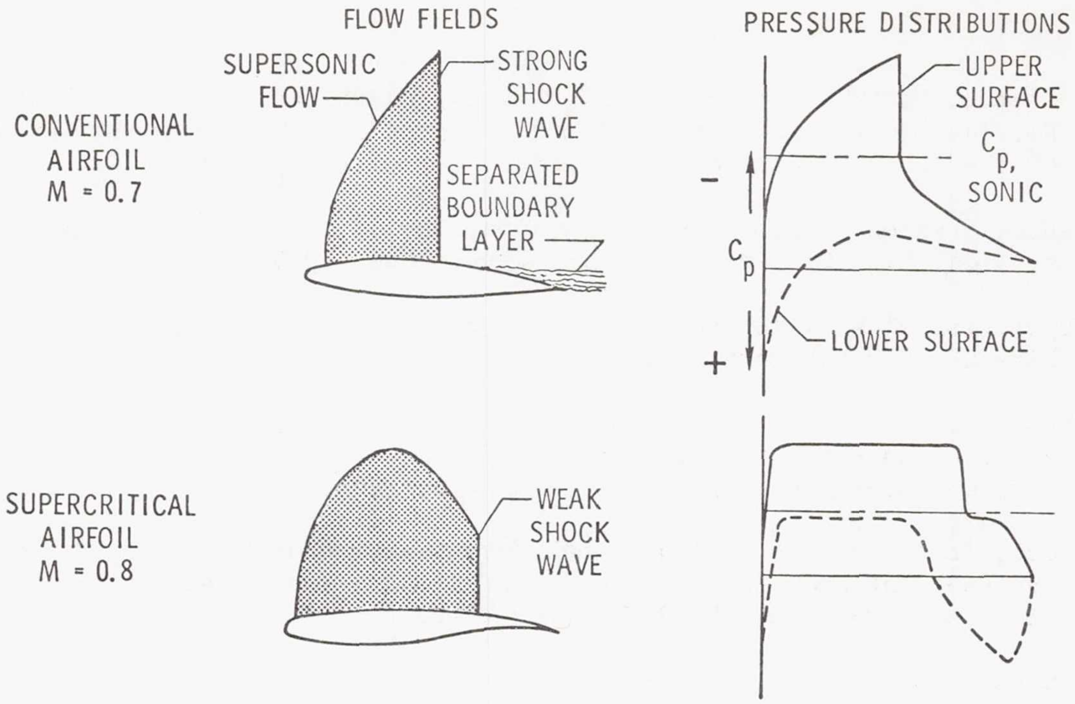


Figure 1.- Supercritical phenomena.

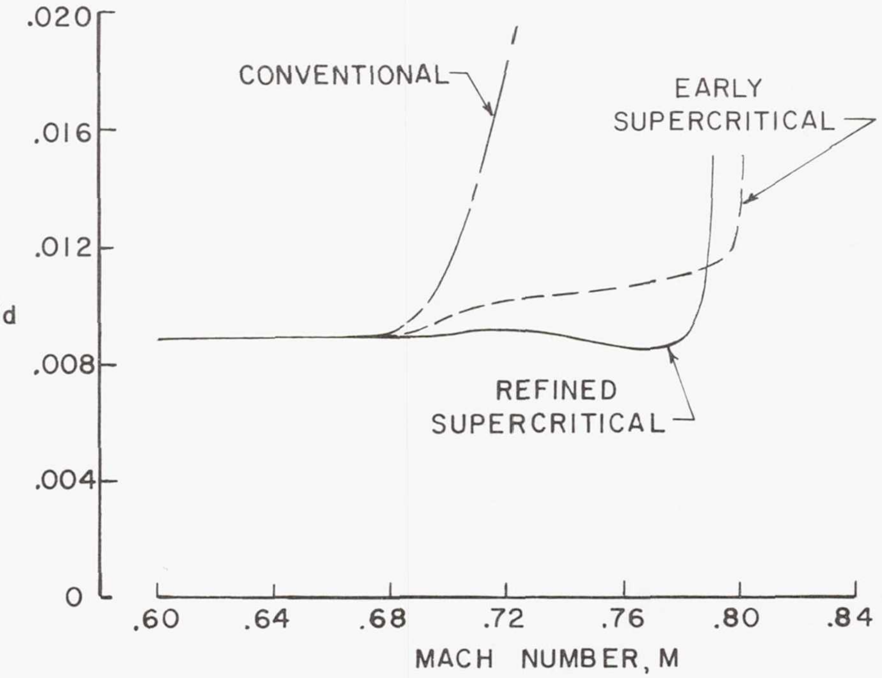


Figure 2.- Drag-rise characteristics for various airfoils. $c_n = 0.7$; $t/c = 0.10$.

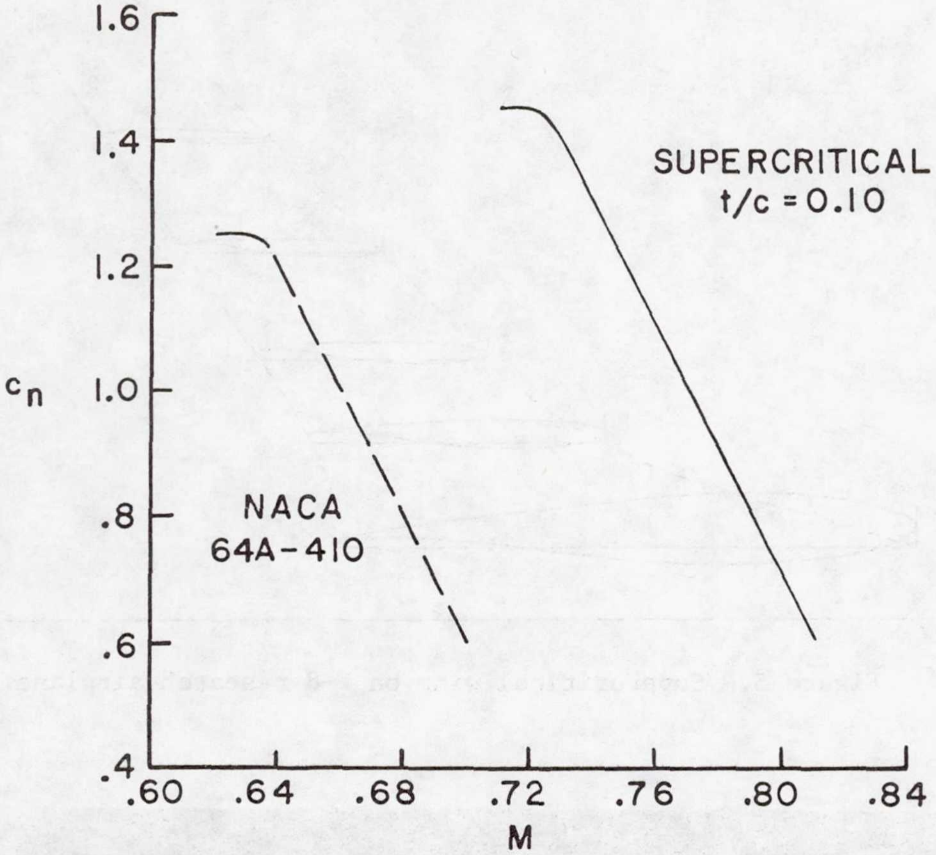


Figure 3.- Onset of drag rise.

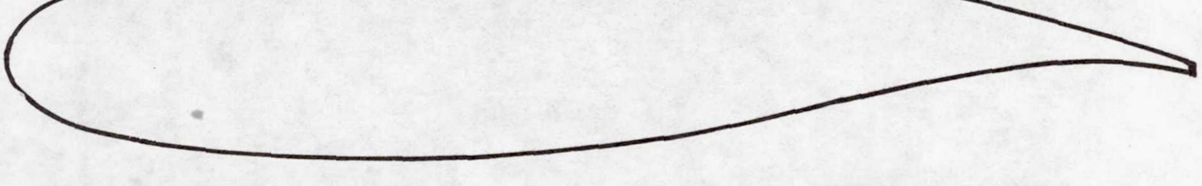


Figure 4.- Thick supercritical airfoil (Palmer of Columbus Division of Rockwell International).

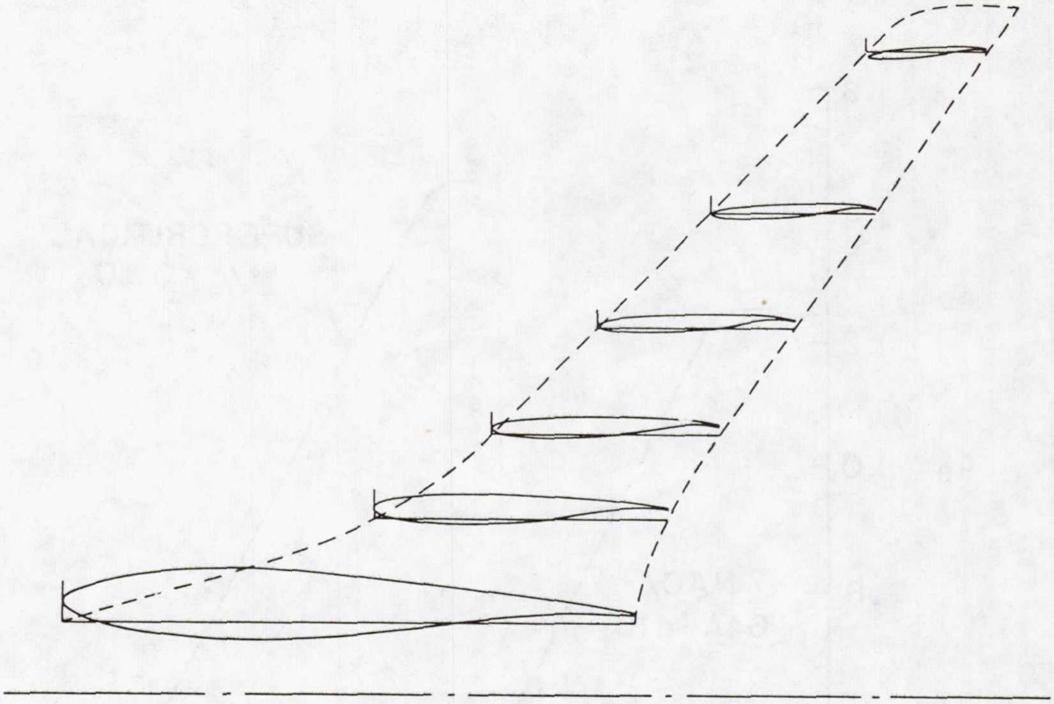


Figure 5.- Supercritical wing on F-8 research airplane.

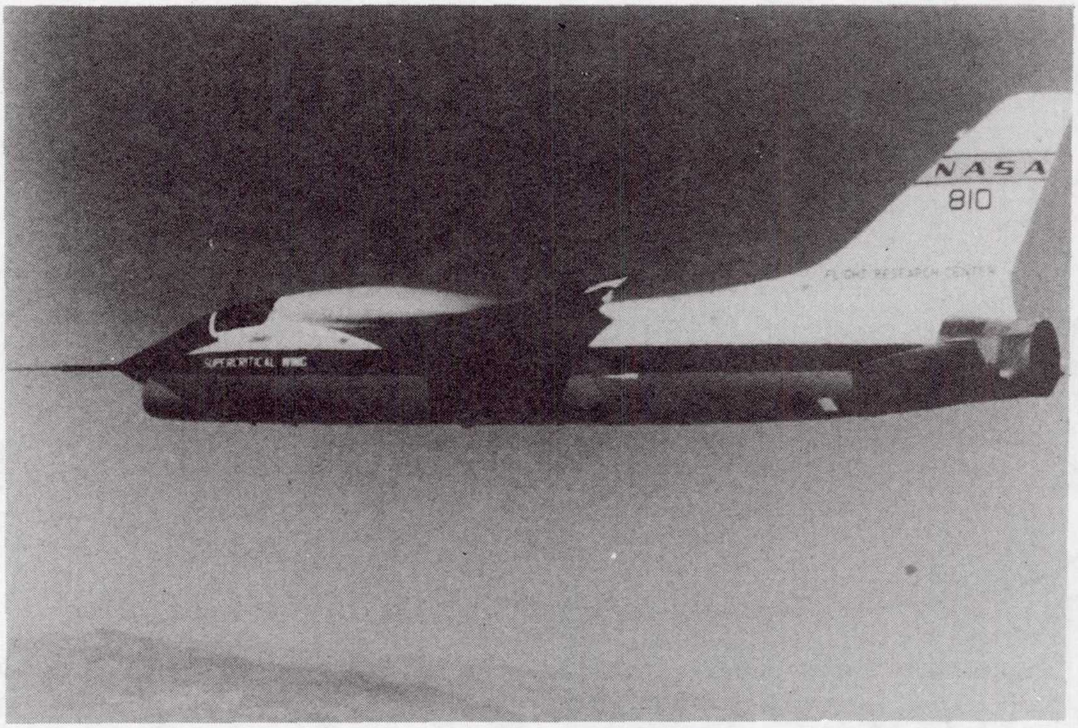


Figure 6.- U.S. Navy F-8 with transport type supercritical wing.

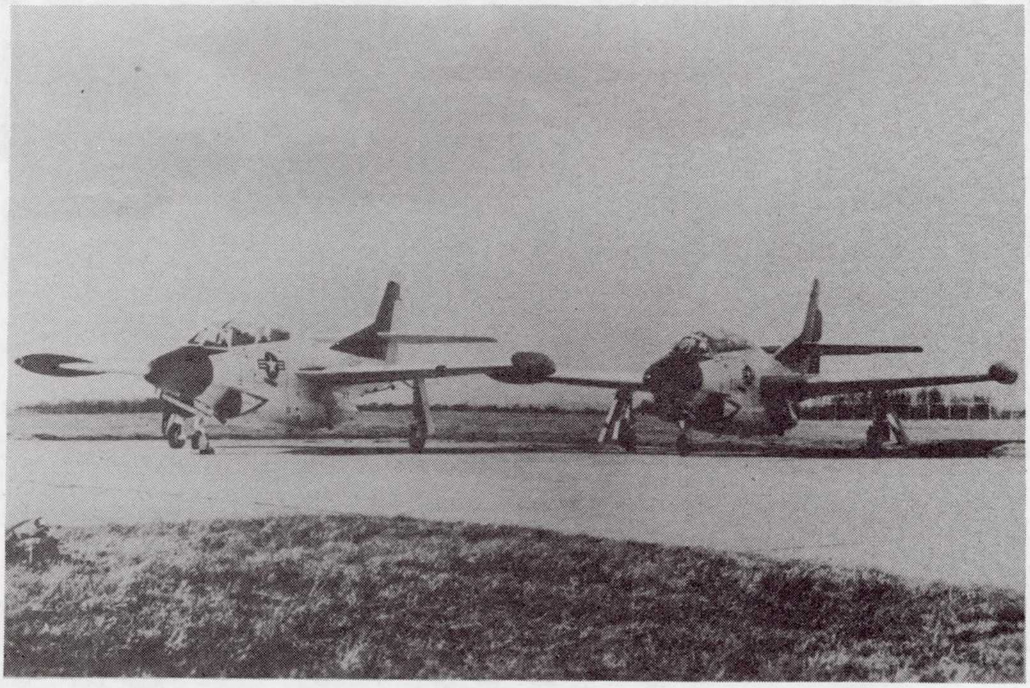


Figure 7.- Comparison of U.S. Navy T-2C airplane with and without thick supercritical airfoil.

Figure 8.- U.S. Air Force F-111 with supercritical wing (TACT).

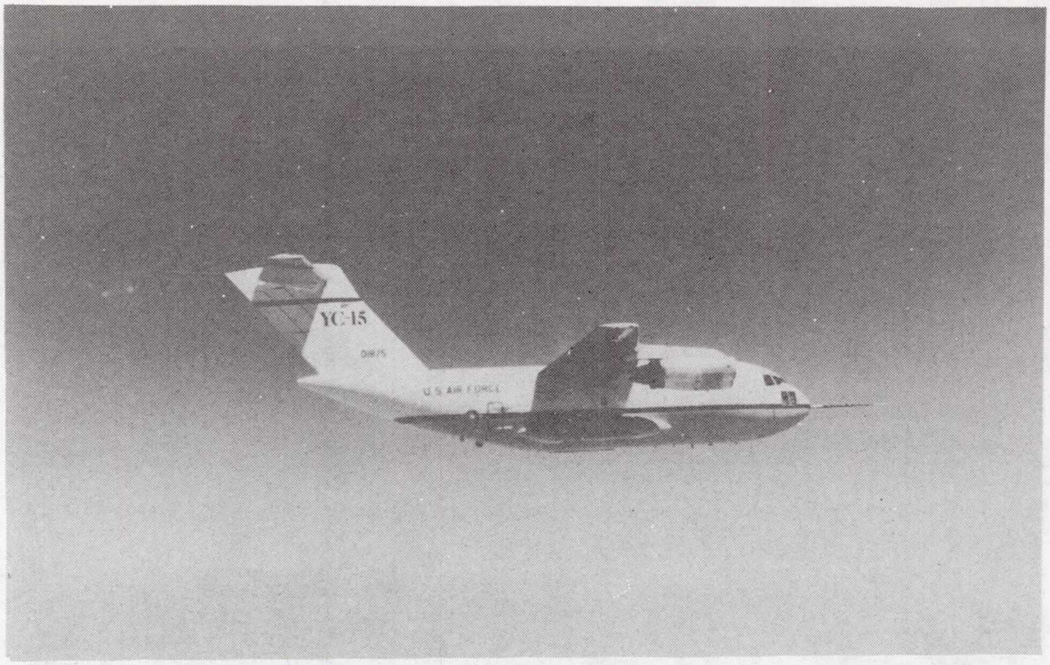
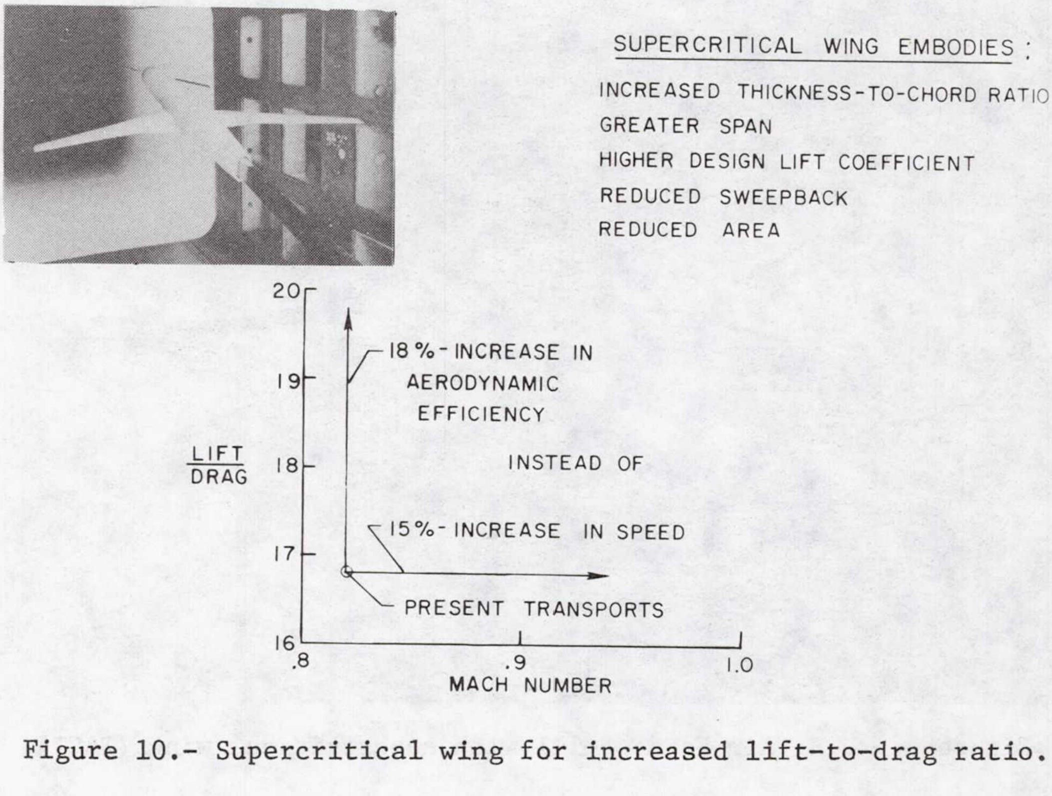


Figure 9.- McDonnell-Douglas YC-15 with supercritical wing.



SUPERCRITICAL WING EMBODIES:

- INCREASED THICKNESS-TO-CHORD RATIO
- GREATER SPAN
- HIGHER DESIGN LIFT COEFFICIENT
- REDUCED SWEEPBACK
- REDUCED AREA

Figure 10.- Supercritical wing for increased lift-to-drag ratio.

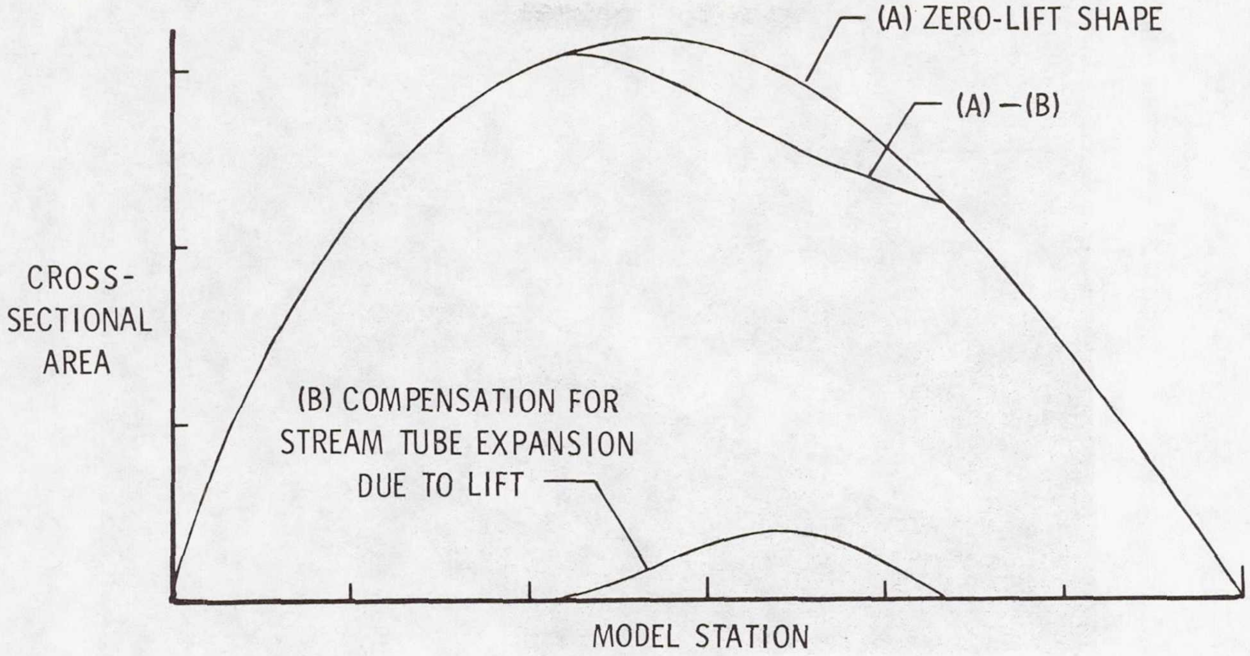


Figure 11.- Second order area-rule considerations.

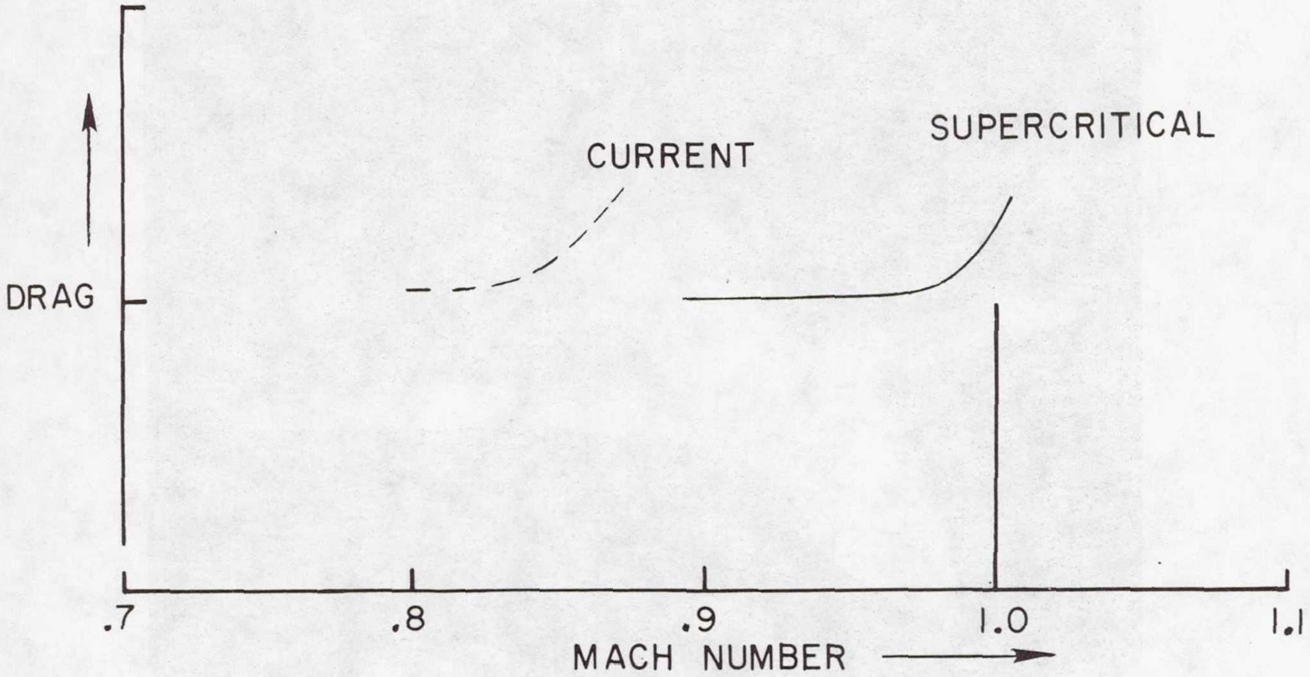


Figure 12.- Drag rise for jet transports (cruise lift).

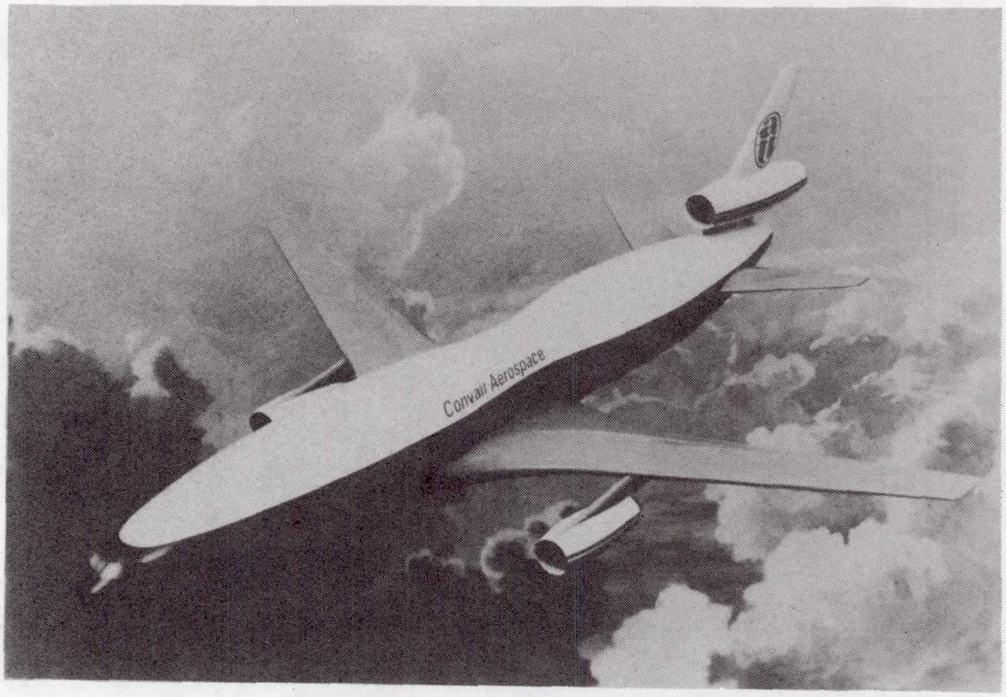


Figure 13.- Artist's concept of a near-sonic transport incorporating a supercritical wing.

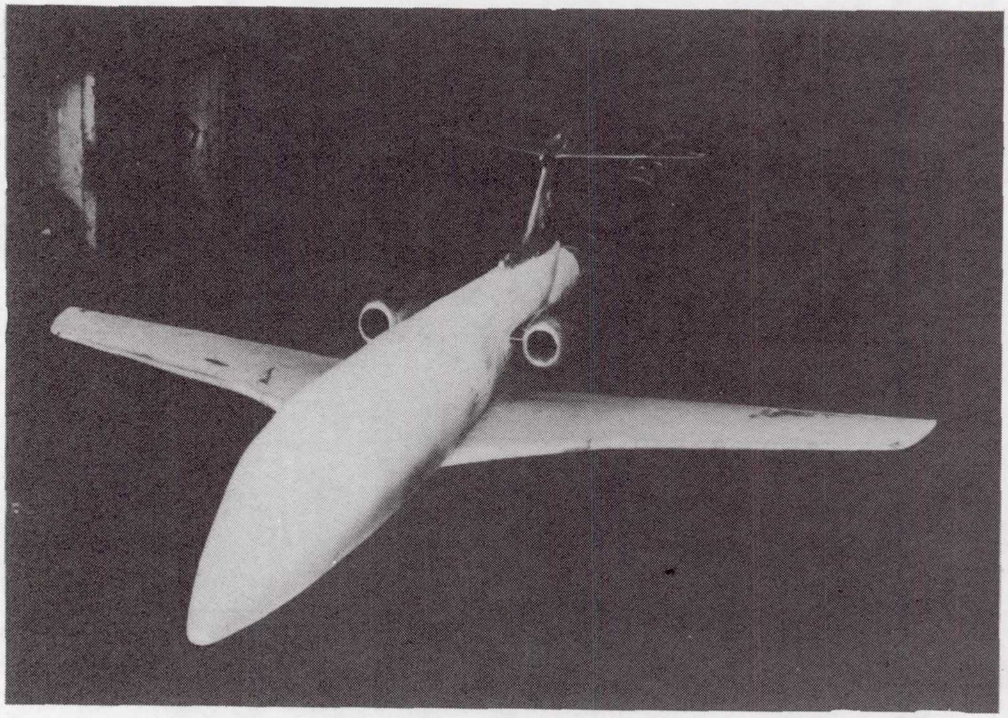


Figure 14.- Model of business jet with supercritical wing.

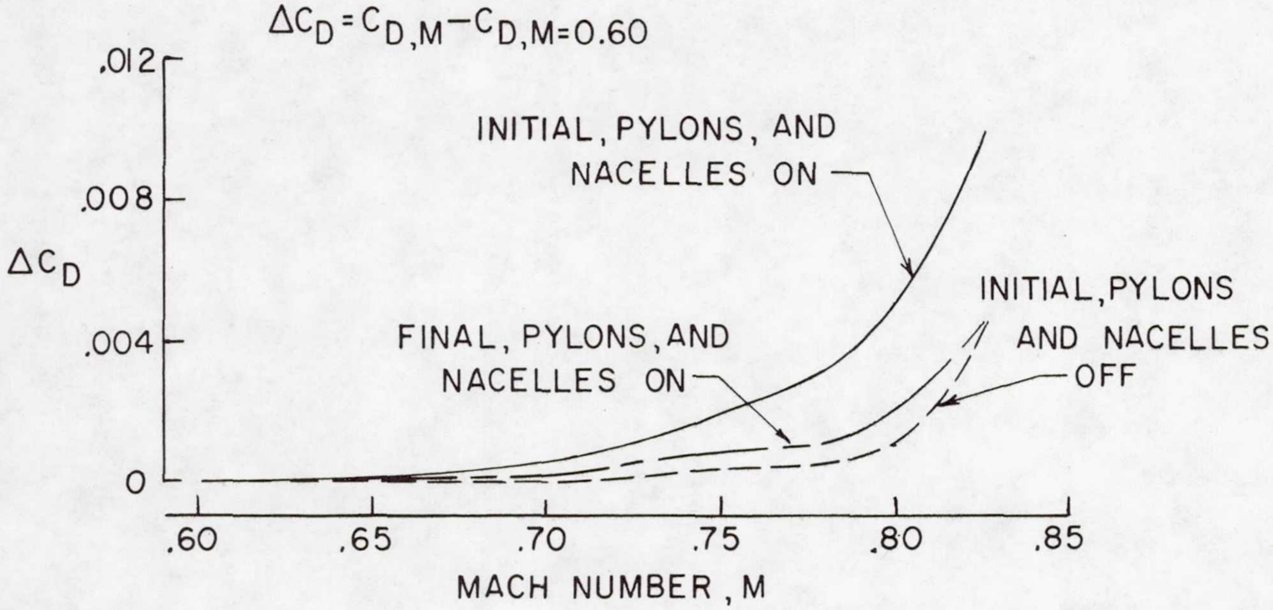


Figure 15.- Effects of wing-root and pylon modifications. Executive-type aircraft; $C_L = 0.25$.