ARTICLE NO. 79-1871R

High-Performance Wings with Significant Leading Edge Thrust at Supersonic Speeds

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A new class of curved leading edge wings with which significant levels of leading edge thrust may be achieved at moderate supersonic speeds is suggested. A recent analysis of the factors limiting such leading edge thrust has led to a new method for the prediction of attainable leading edge thrust from subsonic through supersonic speeds for wings of arbitrary planform. Recent supersonic tests of a new wing shape, which largely meets design criteria given by the new prediction method, give evidence of significant levels of leading edge thrust. The consequent unusually high levels of aerodynamic performance should renew interest in supersonic cruise vehicle design in general and in cruise speed selection in particular.

Nomenclature

b	= wing span
c	= mean aerodynamic chord
C_D	= drag coefficient
C_L	= lift coefficient
$C_{L,\mathrm{opt}}$	= lift coefficient at maximum lift-to-drag ratio
C_m	= pitching moment coefficient
C_A	= axial or chord force coefficient
C_p	= pressure coefficient
k_t	= fraction of full theoretical thrust actually attainable
L/D	= lift-to-drag ratio, C_L/C_D
M	= freestream Mach number
RN	= freestream Reynolds number
sfc	= specific fuel consumption
y	= spanwise distance from reference axis
α	= angle of attack, deg

Subscripts

c	= referenced to mean aerodynamic chord
DES	= design condition
l	= limiting condition
n	= quantities pertaining to a wing section normal to leading edge
max	= maximum value

Introduction

LEADING edge thrust has long been known to be important to the aerodynamic performance of subsonic aircraft. These thrust forces come from very low pressures induced by the high velocities which result as air flows around the wing leading edge from a stagnation point on the wing undersurface. The presence of leading edge thrust to counteract the drag from the remainder of the airfoil permits the high aerodynamic efficiency of the large aspect ratio wings at low speeds. Efforts to extend these benefits to higher speeds have, in part, given rise to the swept wings commonly employed in present-day aircraft. In fact, should the wing leading edge be swept sufficiently behind the Mach line, theory indicates the potential for some thrust in the supersonic speed regime. But until very recently, the amount of leading edge thrust at cruise in configurations suitable for extended supersonic cruising has generally been thought to be insignificant. It is the purpose of this paper to show that such is not the case, that certain wing shapes favor supersonic leading edge thrust and, further, that there is a new method for the prediction of the degree to which it exits as well as the spanwise distribution thereof.

Presented as Paper 79-1871 at the AIAA Aircraft Systems and Technology Meeting, Aug. 20-22, 1979; submitted Sept. 4, 1979; revision received Nov. 29, 1979.

Index categories: Aerodynamics; Computational Methods; Supersonic and Hypersonic Flow.

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Discussion

Experimental/Theoretical Considerations

Figure 1 compares theory with data from tests conducted in the Unitary Plan Wind Tunnel of the Langley Research Center at Mach numbers and Reynolds numbers approximating 2.65 and 4.8 million, respectively. The models represent three supersonic transport concepts. The two on the left are the final competing pair in the United States SST program of a decade ago, while the one on the right is an NASA configuration[1] of the same vintage. All of these are configurations which should not significantly violate the slenderness assumptions of the theoretical methods employed.[2-4]

All three configurations have subsonic leading edges over much of the wing span (i.e., local leading edge swept behind the Mach line) and the leftmost concept has blunt airfoil

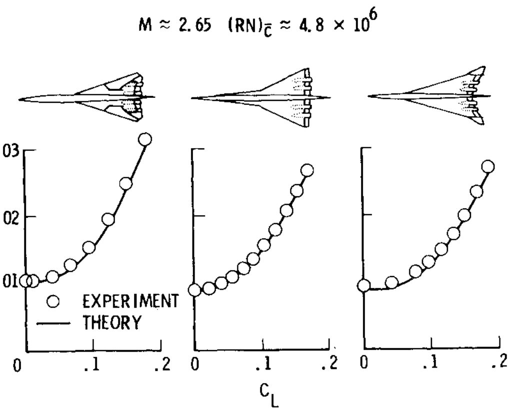

Fig. 1 Experimental/theoretical drag polars of models of supersonic-cruise aircraft.

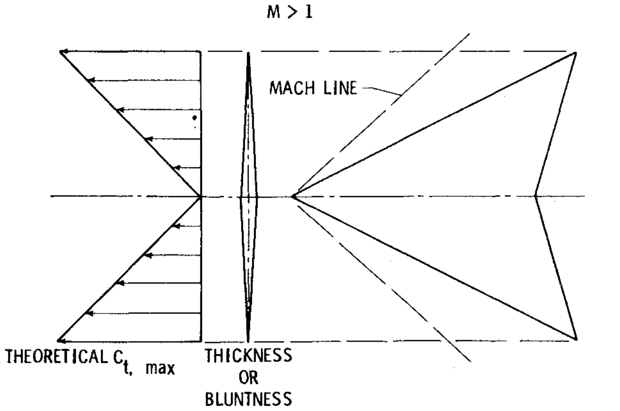

Fig. 2 Maximum theoretical thrust at supersonic speeds for classic arrow wing.

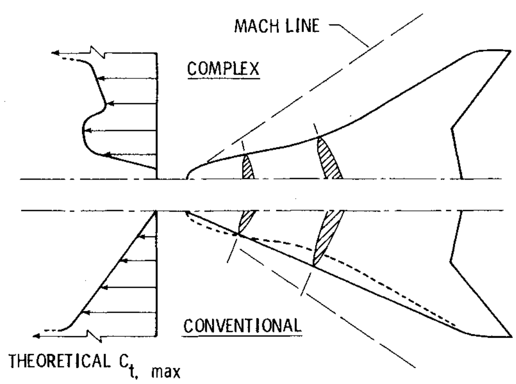

Fig. 3 Thrust and thickness comparisons near wing leading edge.

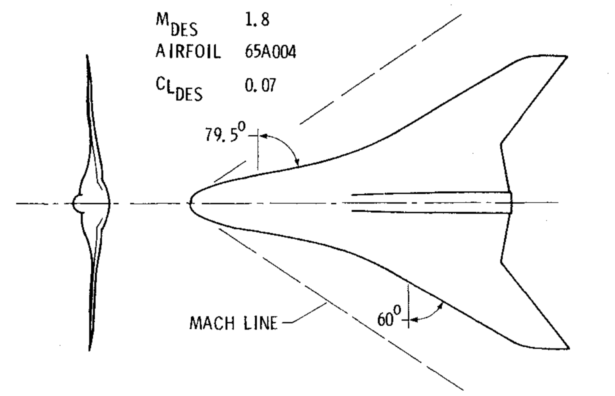

Fig. 4 Wind tunnel model.

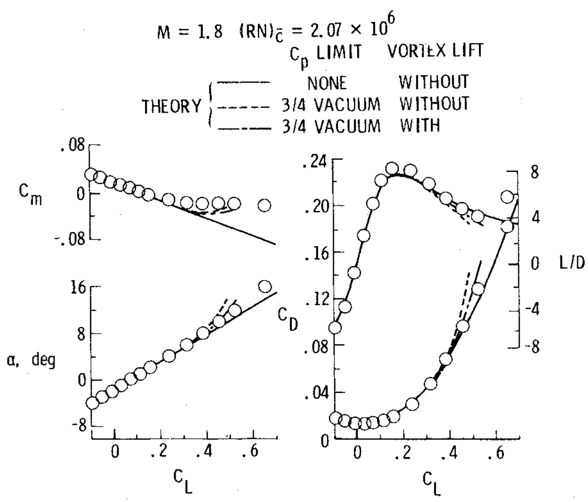

Fig. 5 Experimental/theoretical comparisons of static longitudinal aerodynamic characteristics.

sections, conditions theoretically conducive to the production of leading edge thrust. The good agreement between experiment and theory in which experimental drag generally exceeds theory by small amounts would suggest that the assumption of no leading edge thrust in the calculation methods is justified. These data seem characteristic of supersonic drag polars generally, except at speeds near sonic and for nonslender configurations where violations of the slenderness assumptions tend to obscure such evaluations. In any event, supersonic design and evaluation methods have generally (and, perhaps, conveniently) taken no account of leading edge thrust.

Figure 2 shows one reason why there has been little evidence of supersonic leading edge thrust. Shown for a representative classic subsonic leading edge arrow wing are the spanwise distribution of theoretical full leading edge thrust and the corresponding distribution of thickness or bluntness. Note that where there is maximum potential for thrust, there is little, if any, bluntness or thickness for it to act upon. Figure 3 compares these same characteristics (with some clarifying exaggeration of thickness) for a conventional straight leading edge wing and one of the same overall span and length having a complex leading edge shape. With the exception of the foremost portion of the complex wing, both have all-subsonic leading edges. Again, the straight leading edge wing shows little thrust potential where it has thickness. However, the complex leading edge wing, with its high inboard sweep angles and fuller inboard thickness, exhibits substantial theoretical potential where the geometry favors its attainment. Put another way, there is upwash where there is thickness.

Figure 4 is a sketch of the wind tunnel model corresponding to the complex planform of the previous figure. It is essentially a wing alone with a cylindrical balance housing mounted essentially symmetrically about the wing camber plane and faired smoothly into the forward wing surfaces. The leading edge sweep varies from the parabolic apex to as high as 70½ deg from which it fairs smoothly to a constant 60 deg out to a rounded tip. The design Mach number was 1.8 so that, except at the apex, the leading edge is subsonic. Airfoil sections are NACA 65A004 and, thus, in addition to blunt leading edges, have maximum thickness located between 40 and 45% of the chord. The wing camber and twist is mild, as can be seen in the forward view of the model at zero angle of attack, being designed to provide a lift coefficient of 0.07 at that design attitude. Experimental/theoretical comparisons of the static longitudinal characteristics at the design Mach number and at a Reynolds number of about 2 million, based upon mean aerodynamic chord, are shown in Fig. 5. Compare first the experimental data[5] with the basic no leading edge thrust linear theory[6-8] with neither pressure coefficient limiting nor consideration of vortex lift.[9] Experiment shows nonlinearities in the lift curve and in the pitching moment curve in particular, which are not represented by the theory. In addition, the drag and the lift-drag ratio are poorly represented by the theory in the important optimum lift coefficient region. Imposing an arbitrary limitation of three-quarters of vacuum in theoretical pressure coefficient (which linear theory otherwise might allow to be less than vacuum) results in the dashed curves. We now see breaks in the theory curve, but otherwise little improvement in its representation of experiment. Thus, the theory without pressure limiting (which was used in the wing design) produced a shape which at lift coefficients above 0.3 requires potential flow pressures on the upper surface which are physically impossible to achieve. Assuming that when potential flow cannot be fully maintained, the Polhamus vortex lift analogy[9] applies, normal force increments representing the effects of a separated vortex were applied to the limited linear theory values utilizing a new

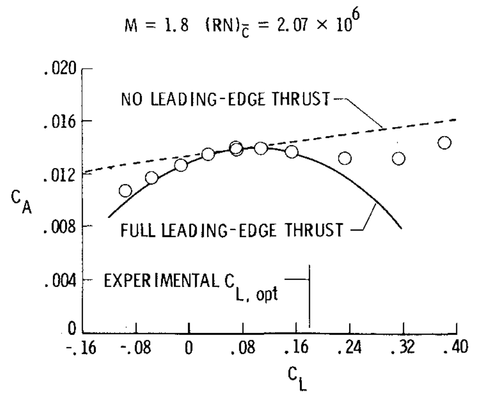

Fig. 6 Experimental/theoretical comparisons of axial force coefficient vs lift.

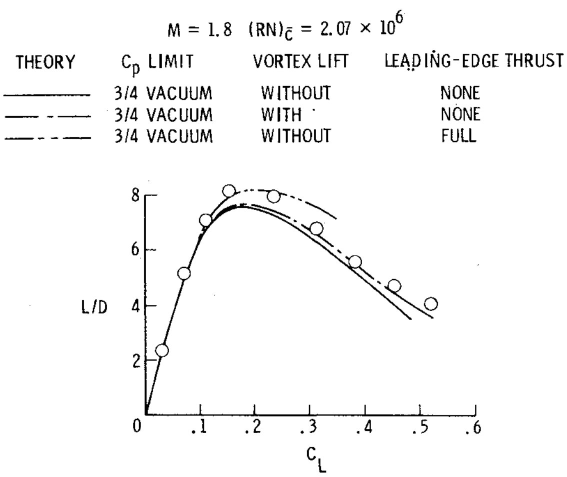

Fig. 7 Experimental/theoretical lift-drag ratios.

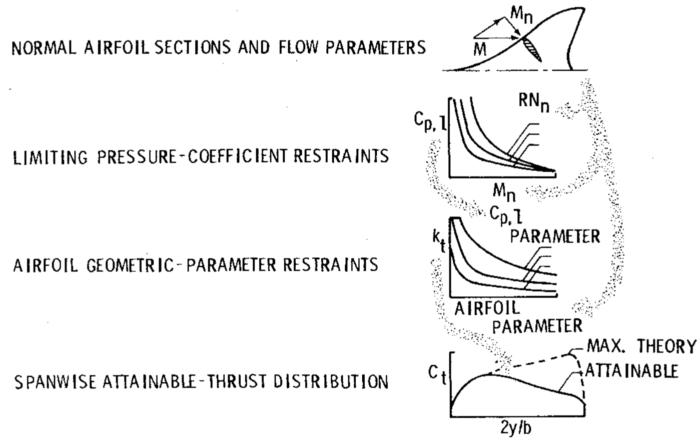

Fig. 8 Key features of attainable thrust prediction method.

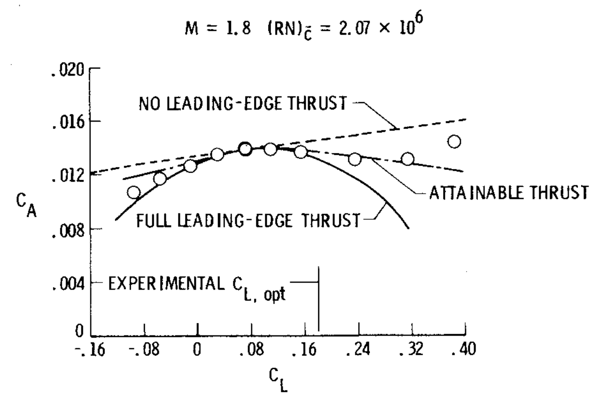

Fig. 9 Comparison of experimental axial-force coefficient with values from original and new attainable thrust theories.

method[10] which provides the necessary theoretical full leading edge thrust values for the arbitrary planform. The resulting curve of limited linear theory with vortex lift, all parameters considered, is certainly an improvement. But there remains a large discrepancy in maximum lift-drag ratio beyond that which might have arisen from the 0.00044 increment by which theory overpredicts zero lift drag. Assuming that prior to manifesting itself as vortex lift that some leading edge thrust might, indeed, have occurred, Fig. 6 was prepared. Here experimental axial force coefficient—a parameter sensitive to leading edge thrust—is compared over the lift range to the theoretical values for full leading edge thrust and for no leading edge thrust. The minimum drag increment mentioned is removed so that experiment and theory coincide at the design lift coefficient (0.07). Significant amounts of leading edge thrust are indicated. The theoretical increment between the full and no leading edge thrust cases were than applied to the limited linear theory values of lift-drag ratio for a summary comparison in Fig. 7. Agreement at maximum lift-drag ratio is much improved. But there remains the problem of predicting whether or not supersonic leading edge thrust occurs, and, if so, how transition is made from the thrusting mode to the vortex lift mode.

New Analytical Method

A study of the factors which place limits on the theoretical leading edge thrust has recently been made, and a method[11] for estimation of attainable thrust has been developed. The key features of the method are depicted in Fig. 8. Simple sweep theory is used to permit the definition of local Mach numbers, Reynolds numbers, and airfoil geometric parameters for flow normal to the wing leading edge. A survey of experimental two-dimensional airfoil data has made possible an analytical representation of limiting pressure coefficient values as a function of the local Mach and Reynolds numbers. These pressure limitations as well as limitations imposed by the airfoil geometric parameters are then taken into account in correlation equations derived from a computer-implemented study of theoretical airfoil aerodynamics to provide estimates of a factor k_t, representing the fraction of full theoretical leading edge thrust actually attainable. With this factor and the arbitrary planform (full theoretical leading edge thrust method[10]), the spanwise distribution of attainable thrust is found. Lift and drag relationships in the method are compatible with the Polhamus leading edge suction analogy[9] for fully detached vortex flow, when the analogy is taken to be the limiting case of a gradual rotation of the suction vector that occurs as leading edge thrust is lost. Thus the method does provide a calculative means for transitioning from the thrust mode to that of vortex lift.

Application of the new method to the present set of data provides the axial force comparison shown in Fig. 9 where the new, attainable thrust curve provides a reasonably good representation of experiment in the positive lift range up to lift coefficients of 0.3 or so. Returning via Fig. 10 to the lift-drag ratio comparisons between theory and experiment, the attainable curve is seen to agree with the full-thrust values in a very limited low lift range. From the low lift coefficient values of such agreement to the highest values shown, the new method provides that less and less of the leading edge force be manifested as thrust, and more and more be manifested as vortex lift. The inset flow-visualization photographs, taken at the conditions represented by the darkened symbols, are included to provide an understanding of the flow physics at those points. The upper pair of photographs are of the upper surfaces of the model with a fluorescent oil coating, which, under the action of the flow, has essentially stabilized at each

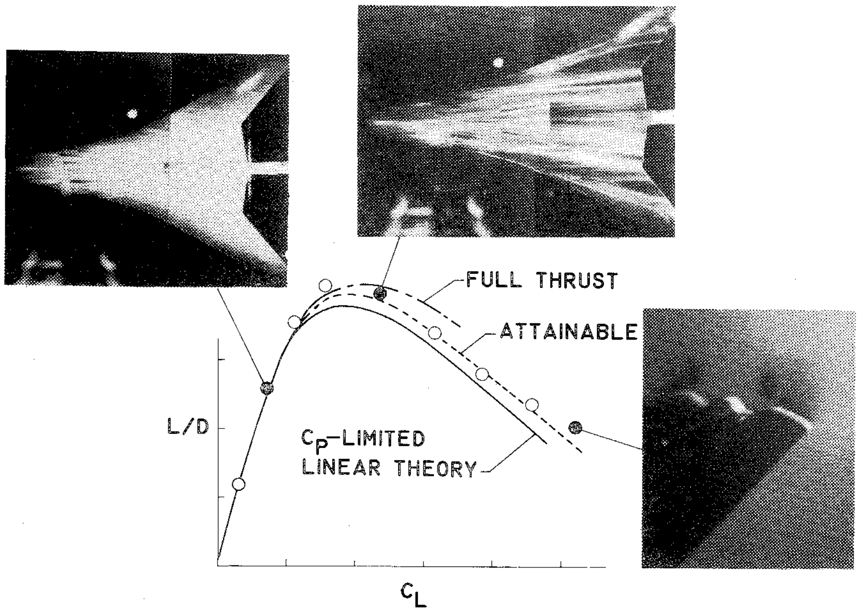

Fig. 10 Comparison of theories with both qualitative and quantitative experimental data.

of the two conditions. The picture at the right is taken from above the right rear quadrant of the model as it is immersed in humid, partially condensed flow and illuminated by a thin fan of intense flight positioned normal to the flow. Strong vortices appear at this high lift condition as the pair of dark circles located above the wing surface about midway between the wing leading edges and the model plane of symmetry. Thus the upper surface flow appears to vary from the classic potential flow condition at the lift coefficient for which the wing camber was designed, through a condition in which there is a mixed flow including some vorticity, to the condition at high lifts in which there is strong fully separated vorticity located well inboard of the leading edge. In any event, the modified linear theory method, which attempts to account for these nonlinear types of flow, provides, in addition to an indication of significant amounts of leading edge thrust, a substantially improved representation of the experimental results.

Conclusions

Significant levels of leading edge thrust have been measured at supersonic speeds. A new methodology is now available for prediction of the attainable leading edge thrust and/or that component of thrust which acts as vortex lift. There is a new class of supersonic wings which matches the theoretical thrust distribution potential with supporting airfoil geometry (that is, which provides for upwash where there is airfoil bluntness). High maximum lift-drag ratios at higher lift coefficients should result. With both thrust potential, and the prospect of attainment of substantial amounts thereof, increasing with decreasing supersonic Mach numbers, improvements in range factor ($M \cdot L/D \div$ sfc) should give rise to serious consideration of lower supersonic cruise speeds (of the order of Mach 2 or less) which also offer more speed compatible propulsion systems and airframes.

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