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Aerodynamics of Powerplant Installation on Supersonic Aircraft

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Simple ideas derived from theoretical studies are utilized to explain the action of an engine nacelle upon a wing in supersonic flow. The engine installation is shown to influence both the wave drag due to thickness and the drag due to lift. Available theoretical procedures make it possible to estimate the forces on a wing due to the combined action of several nacelles, and results of theoretical calculations are compared with supersonic wind-tunnel-test data. The effects of the relative location of nacelles and the effects of nacelle shape and size on the lift, drag, and pitch characteristics of wind-tunnel models are presented and discussed. Experimental results are used to demonstrate that the camber and twist of the wing should be designed by taking into account the effects of the flowfield from the nacelles. It is indicated that designing for low drag requires consideration of the lift distribution on the airplane and a knowledge of viscous effects.

Nomenclature

C_L = lift coefficient
C_D = drag coefficient
C_M = pitching-moment coefficient
C_{Df} = skin-friction-drag coefficient
ΔC_{DI} = drag coefficient of isolated nacelle
ΔC_{LN} = nacelle lift increment = $C_{L\text{nacelles on}} - C_{L\text{nacelles off}}$ at constant angle of attack
ΔC_{DN} = nacelle drag increment = $C_{D\text{nacelles on}} - C_{D\text{nacelles off}}$ at constant lift coefficient
S_W = wing area
ΔS = (nozzle area-inlet area)
α = angle of attack
Θ = camber line slope

Introduction

THE purpose of this paper is to present the effects of engine location on the external efficiency of supersonic airplanes. Variations in the location of the engine nacelles are responsible for large changes in drag, Fig. 1. Systematic studies of nacelle placement are therefore an important part of airplane design. In order to carry out these studies, it is necessary to understand the interference forces that produce the drag changes.

It is a distinctive feature of supersonic flight that the zone of influence of a body contracts laterally into a narrow space around the body. This property is the cause of significant interference forces between the major components of an airplane. A study of interference has for its objective drag reduction by a suitable arrangement of airplane components. Much has been written on favorable interference,[1-4] and a number of configurations based on favorable interference have been proposed. Although the development of practical airplanes from these rather theoretical configurations has not been obvious, the physical ideas put forward in the literature have been of assistance in studies of engine-airplane integration.[5]

In this paper we shall discuss the physical principles that have been brought forward by theoretical studies and we shall use these principles to isolate and define various interaction forces between an engine nacelle and a wing. Different aspects of the aerodynamic problem associated with nacelle installation will then be examined, using both theoretical and experimental results.

Wing-Nacelle Interactions

Lift Interference

In supersonic flight the zone of influence of a body is concentrated in a narrow space contained within a train of shock waves. To illustrate this we have shown in Fig. 2 a nacelle in a supersonic stream. As is often the case, the inlet area of the nacelle is smaller than the exit area, and the area grows progressively between the inlet and the exit. The incoming flow is compressed at the inlet and the resulting high-pressure field is contained between the front shock wave and an expansion fan from the shoulder of the nacelle. If a wing is now placed above the nacelle to intercept this flowfield, a lift force will be carried by the wing. This is illustrated schematically in Fig. 2. If the nacelle is moved axially relative to the wing, the in-

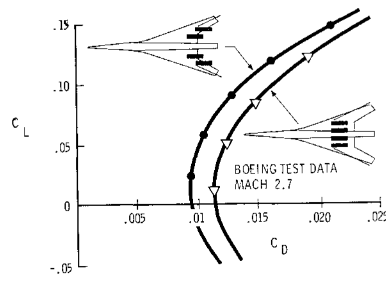

Fig. 1 Effect of powerplant installation on cruise drag.

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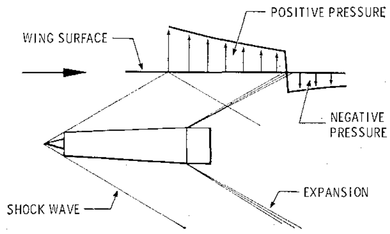


Fig. 2 Interference lift.

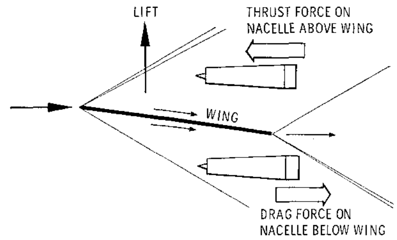


Fig. 5 Effect of lifting wing on nacelle drag.

duced lift will be greatest when all the positive pressure field is reflected back; the lift will diminish as the front shock from the nacelle moves toward and then ahead of the wing leading edge.

Wing Thickness and Camber Interference

The interference pressure force from the nacelle on the wing will have an axial (drag or thrust) component any time the wing surface is at an angle to the local stream. Figure 3 shows the effect of increasing the thickness of the wing on the nacelle drag increment. When the wing has no thickness, this drag increment is that of the isolated nacelle. As the wing thickness is increased, the drag increases or decreases, depending on the location of the nacelle in relation to the wing. Two examples are shown in Fig. 3: when the front shock from the nacelle acts behind the point of maximum thickness of the wing, the interference drag diminishes; when the induced pressure field is in front of the maximum thickness, the interference drag increases. To a first order, the rate of change of interference drag is linear with thickness. The total drag, however, includes the drag of the wing, which increases with the square of the thickness. The effect of wing camber on interference drag is qualitatively similar to the effect of thickness, Fig. 4. Note that camber changes that reduce interference drag result in a loss of wing lift. The best compromise between these effects must be sought.

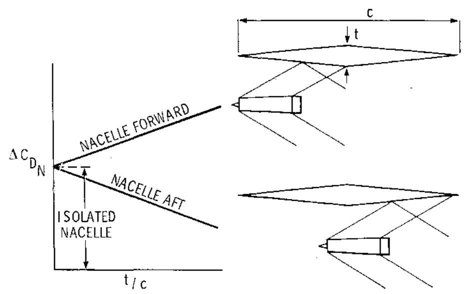


Fig. 3 Nacelle effect on wing thickness.

Effect of the Wing on the Nacelle

The disturbance that the wing produces also is contained within a shock-wave system. Figure 5 shows that, when a nacelle is placed in the flowfield of a wing at angle of attack, the sign of the interference force on the nacelle will be determined by, whether the nacelle is located above or below the wing. Figure 6 shows that, when the effect of the thickness of the wing is considered, it is the fore or aft location of the nacelle that determines the sign and magnitude of the interference force.

Three-Dimensional Effects

The trace of the pressure disturbance from a body in the plane of an intercepting wing surface is shown in Fig. 7. The trace of the front shock wave is approximately parabolic, and the interference forces will depend on the location of the front shock on the planform of the wing. Figure 8 shows the combined effect of four nacelles on a wing. For this example, it is seen that a relatively large amount of interference lift would be generated, since the pressure pattern from the nacelles is well contained by the wing.

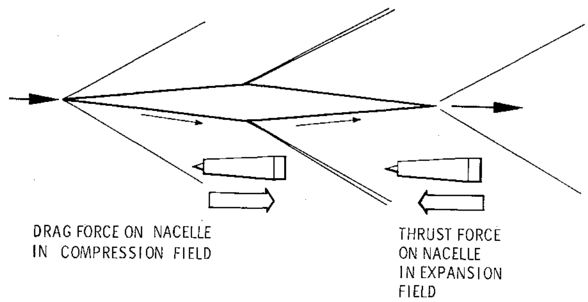


Fig. 6 Effect of wing thickness on nacelle drag.

The interference pressure distribution for the example shown has been calculated by methods similar to those described in Ref. 6. It was found that the interference lift would produce about 10% of the wing lift at the design condition. The shading in the plane of the wing is an indication of the magnitude of the interference pressure, the darkest shade indicating the greatest pressure.

Test-Theory Comparisons

Theoretical methods are available to estimate the magnitude of wing-nacelle interference forces. These methods are

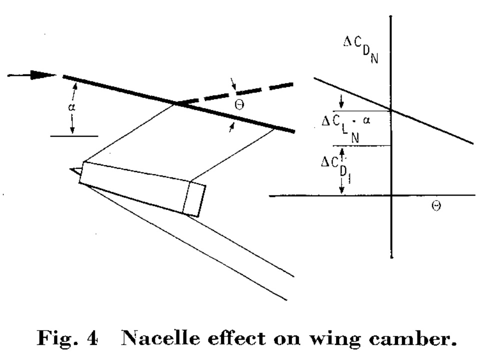


Fig. 4 Nacelle effect on wing camber.

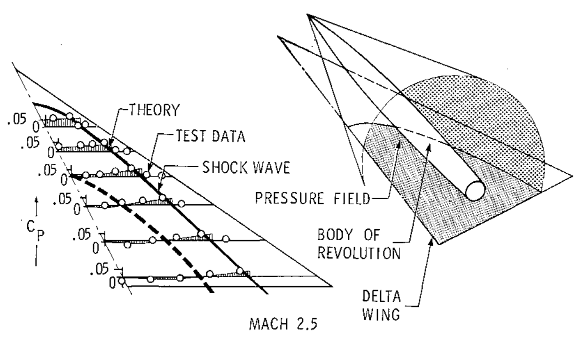


Fig. 7 Pressure field of a body of revolution.

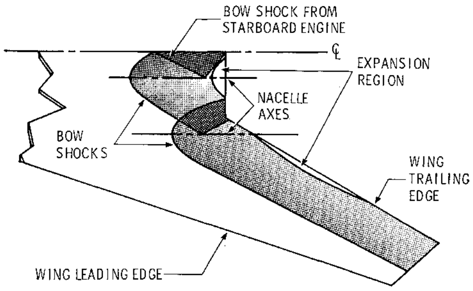


Fig. 8 Combined nacelle pressure fields.

generally based on small perturbation theory, which allows the superposition of flowfields calculated separately for individual airplane components. Figure 9 compares the results of such calculations with experimental results. In this example the nacelles have been located below the wing and behind its line of maximum thickness. Test and theory are compared for the change in lift and drag due to the addition of nacelles to a wing body in supersonic flow. It is seen that it is possible to estimate adequately the lift increment as well as the change in drag coefficient at various lift coefficients.

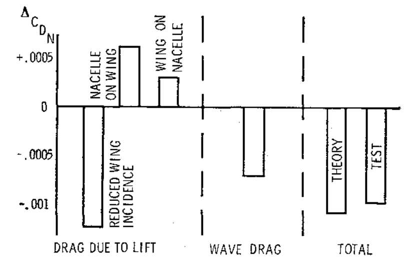
Theory allows us to analyze the drag into components, Fig. 10. It is seen that the net drag results from a balance of interference increments, some of which are favorable and others adverse. The lift that the nacelles generate on the wing results in a favorable effect, because the wing does not have to generate this lift by itself and can operate at lower angle of attack. On the other hand, the interference lift from the nacelles has to be carried by the wing, and if the wing is at an angle of attack the pressures that produce the lift will have a drag component.

In Fig. 10, the wing considered had an arrow planform with highly swept subsonic leading edges and nacelles located toward the rear of the wing. It is known[7] that such a planform has lower drag due to lift when the centroid of its lift distribution is ahead of the aerodynamic center, and it was thus found beneficial to reflex the camber of the wing in the region of the impingement of interference pressures. The drag term caused by the direct action of these pressures on the wing could thus be minimized.

Another adverse effect, indicated in Fig. 10, is that of the lifting wing on the nacelle. Generally speaking, this effect is always present when nacelles are located below a lifting wing. Theoretically, this effect could be reduced by pulling the nacelles away from the region of influence of the wing, but it has been found in practice that the drag caused by the struts or pylons, that then become necessary, more than offsets the possible drag reduction.

Finally, Fig. 10 also indicates drag reduction from favorable wave drag interference. In the case examined, this resulted

Fig. 10 Analytical breakdown of interference drag.



from having a favorable nacelle pressure field act behind the maximum wing thickness. The possibility of drag reduction by this method has been well-explained in Ref. 8.

Aerodynamic Aspects of Nacelle Installation

Effect of Nacelle Location

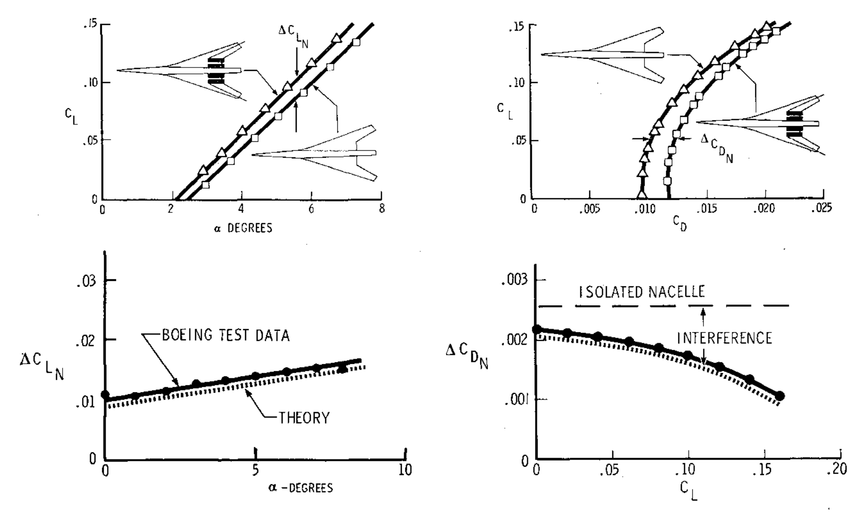
A typical effect of nacelle location on the drag and pitch characteristics of a given wing is shown in Fig. 11, which illustrates experimental results obtained with two different nacelle arrangements. When the outboard nacelle was moved ahead of the leading edge, its pressure field impinged ahead of the wing maximum thickness and the wave drag was increased. At the same time, this nacelle generated lift, as evidenced by the pitching-moment data, and the drag due to lift was improved, leading to drag reduction at the higher lift coefficients. The example illustrates the interaction of various interference forces.

Effect of Nacelle Shape and Location

Two nacelles that may be considered typical for flight in the Mach 2.0 to 3.0 range are shown in Fig. 12. Both are shown as having the same capture area and maximum diameter, but one has a slightly underexpanded nozzle whereas the nozzle of the other is fully expanded. If interaction effects were not to be considered, the first nacelle would show superior performance because of its lower nozzle weight and external drag. However, the nacelle with the larger nozzle produces larger regions of positive pressure which may be captured by the wing and reduce drag. In consequence, the net performance of each of these nacelles will depend on integration into the design of the airplane with due regard to interference effects.

In Fig. 13, wind-tunnel-test results are shown for each nacelle attached in turn to the same wing at Mach 2.7. The nacelles are shown located below the centroid of the wing so that the pressure field falls both fore and aft of the maximum wing thickness and also partially ahead of the wing leading edge. Interference forces are small, and there is little, if any, drag change between the two nacelle installations. In Fig. 14, how-

Fig. 9 Comparison of theory and experiment.



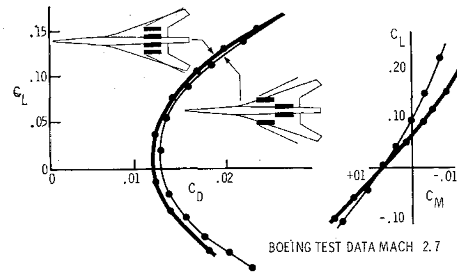


Fig. 11 Effect of nacelle location on drag and pitching moment.

ever, the nacelles have been moved towards the rear of the wing, where wave drag interference is favorable and nacelle lift can be captured. The nacelle with the larger nozzle, which produces stronger interference forces, is clearly superior in this position.

Figure 15, then, compares the nacelle with the small nozzle located in the forward position to the nacelle with the larger nozzle in the rear position. It is seen that by combining a favorable nacelle shape with a favorable nacelle location significant reductions in drag are possible.

Effect of Nacelle Toe-In

With the wing at a lifting condition, drag reduction is possible by aligning the nacelles into the local stream direction.

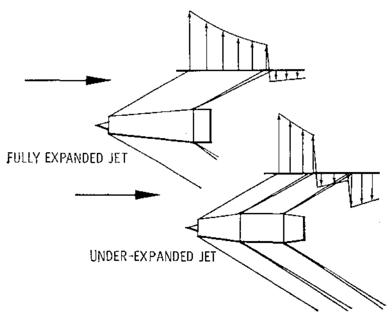


Fig. 12 Effect of nacelle shape on lift distribution.

With the nacelles under the wing, generally speaking, this requires nacelle toe-in. Depending on nacelle location, further drag improvement is possible by producing on the nacelle a small side force that has a thrust component. Figure 16 shows test data comparing nacelles with and without toe-in. The pitch and drag data indicate that toe-in has resulted in favorable lift and drag interference.

Design of Wing Camber in the Presence of the Nacelle Flowfield

One of the more interesting aerodynamic aspects of the design of supersonic powerplant installations is the determination of the wing camber and twist. Figure 17 shows the results of an experimental study designed to investigate the effect of trailing-edge-camber changes upon the drag, at cruise lift coefficient, of a wind-tunnel model both with and without nacelles. The results of the tests indicate that the least drag for each condition is achieved with different camber designs. In particular, the data show that for the model with nacelles-on, a larger amount of trailing-edge reflex is required. This is easy to understand in light of the discussions in the preceding sections. At a constant lift coefficient, the general effect of camber and twist variations is to change the drag of a wing by redistributing lift on its planform. The most desired camber is the one yielding the lowest drag within some constraints on pitching moment. When the nacelles add lift to the wing, a redesign of camber is in order, and, generally, the wing-surface slope will need to be reduced in a region of interference lift. However, reduction of wing-surface slope (negative camber or reflex) leads in turn to a loss in wing lift, and an efficient aerodynamic design will have the interference pressure field act upon that region of the wing planform where the local lift slope is smallest. On a wing with swept leading edges this region is inboard toward the rear of the wing. A wing-nacelle combination with the nacelle lift added in that region will then benefit from a redistribution of wing lift towards the wing leading edge.

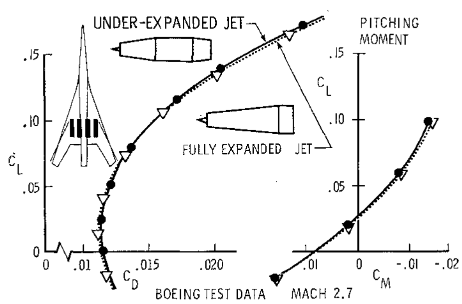


Fig. 13 Effect of nacelle shape at forward location on wing.

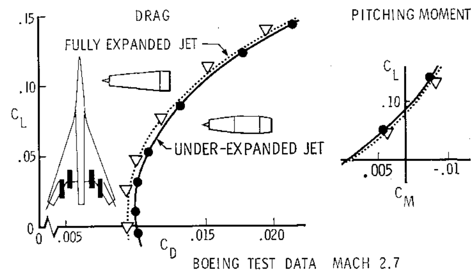


Fig. 14 Effect of nacelle shape at aft location on wing.

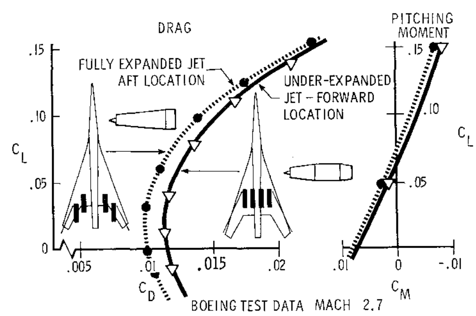


Fig. 15 Combined effect of nacelle shape and location.

Effect of Nacelle Size

The aerodynamic effect of nacelle size will depend on the location of the nacelles on the airplane, but if the nacelles are located in a region of favorable interference, drag reductions will be obtained by increasing the size of the nacelles. The results of theoretical calculations illustrating how nacelle size and

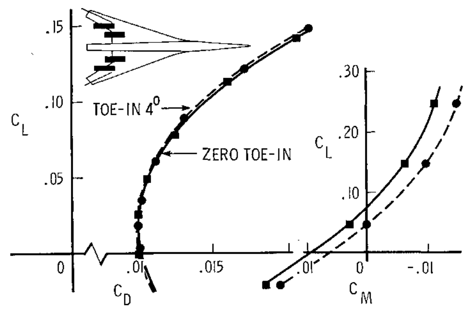


Fig. 16 Effect of nacelle toe-in.

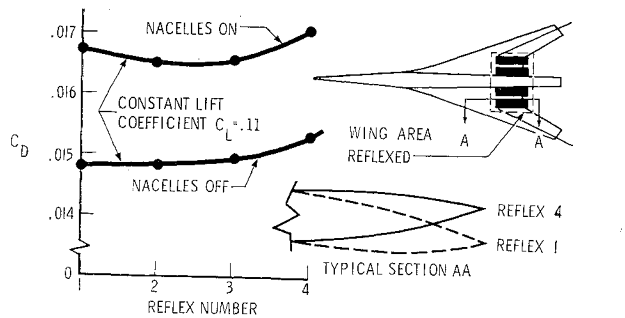


Fig. 17 Effect of trailing-edge camber on cruise drag coefficient.

trailing-edge reflex affect the drag at a constant lift coefficient are shown in Fig. 18. Provided the amount of reflex is increased simultaneously with nacelle size, cruise drag diminishes. A theoretical minimum has not been found within the range of nacelle sizes shown in Fig. 18, but a practical minimum will be achieved before the increase in lifting pressures near the leading edge (caused by the increasing reflex) becomes excessive and leads to adverse viscous effects.

Design Mach Number

The design Mach number influences powerplant integration chiefly in two ways. First, since nacelle pressures propagate approximately along Mach lines, the wing sweep should vary with design Mach number if maximum beneficial effects are to be derived from the nacelle pressures. Second, the internal design of the powerplant requires changes in the external contours, and this in turn may affect location on the airplane. For example, nacelles designed for low supersonic speeds tend to be barrel shaped, having maximum diameters greater than either the inlet or the nozzle. Such a nacelle generates a strong bow shock, followed by an expansion to low pressure at the rear.

Generally speaking, the results presented previously have been verified from about Mach 1 to Mach numbers just in excess of 3. The validity of the physical ideas is, of course, valid beyond Mach 3.

Concluding Remarks

We have discussed the engine installation on supersonic airplanes from the point of view of external aerodynamic efficiency. This is not the only point of view. In practice, additional factors have to be considered,[9] and the scope of nacelle location studies is considerably wider than has been indicated. Some of the many other important factors are the internal performance of the propulsion system, the effects of engine location on air plane balance, structural design for low weight, and the effects of nacelle location on the high-lift system.

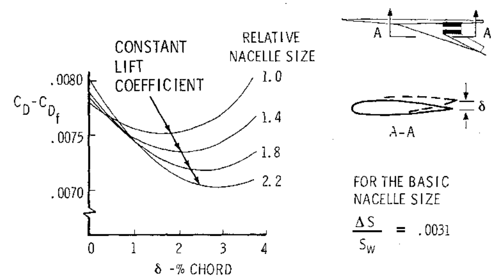


Fig. 18 Theoretical effect of nacelle size.

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