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APPLICATION OF POWERED-LIFT CONCEPTS FOR IMPROVED CRUISE EFFICIENCY OF LONG-RANGE AIRCRAFT

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SUMMARY

The present paper summarizes results of recent studies conducted at the NASA Langley Research Center to explore the use of powered-lift concepts for improved low-speed performance of long-range subsonic and supersonic cruise vehicles. The results indicate that powered lift can provide significant improvements in low-speed performance, as well as substantial increases in cruise efficiency and range for both subsonic and supersonic cruise configurations.

INTRODUCTION

The NASA Langley Research Center is currently investigating the use of powered-lift concepts for improved low-speed performance of long-range subsonic and supersonic cruise aircraft. This research has been directed toward concepts which may provide substantial increases in lift for improved take-off and landing performance and, further, which may provide better engine-airframe matching for improved cruise efficiency and range.

The present paper summarizes results of recent studies of powered-lift concepts, conducted in the Langley V/STOL and full-scale tunnels. In particular, the paper discusses (1) the application of the over-the-wing blowing (OTWB) concept to an advanced subsonic cruise configuration and (2) the application of OTWB and thrust vectoring concepts to an advanced supersonic cruise configuration.

SYMBOLS

C_L	lift coefficient
$C_{L,\Gamma}$	additional circulation lift
C_m	pitching-moment coefficient
C_μ	thrust coefficient
D	engine nozzle diameter (see fig. 5)

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h	height of engine nozzle above wing (see fig. 5)
i_c	incidence of canard
S	wing area
S_t	tail area
T	thrust
W	aircraft weight
α	angle of attack
δ_f	flap deflection angle

Abbreviations:

BLC	boundary-layer control
OTWB	over-the-wing blowing
USB	upper-surface blowing

POTENTIAL BENEFITS DERIVED FROM POWERED-LIFT CONCEPTS

One of the fundamental considerations in the design of a cruise efficient aircraft is the sizing of the configuration with regard to wing area and installed thrust requirements. It is recognized that the sizing process involves considerable compromise, and that low-speed performance plays a key part in the trade-off.

Presented in figure 1 is a classical "thumb print" plot which shows the variation of range with installed thrust-to-weight ratio T/W and wing loading W/S. Also shown in this figure is a typical take-off field length constraint which emphasizes the impact that low-speed performance has on engine-airframe sizing. The important point illustrated by figure 1 is the fact that for a specified configuration, optimum range is obtained with relatively low values of T/W and relatively high values of W/S, and that increasing T/W or reducing W/S from the optimum values in order to meet the take-off field length requirement results in a substantial reduction in vehicle range (or in an increase in aircraft weight, cost, and fuel consumption to achieve a given range).

Figure 2 illustrates the influence of take-off lift coefficient, T/W, and W/S on take-off field length requirements. This relationship was obtained from an empirical study and is discussed in detail in reference 1.

From figure 2 it is seen that a specified take-off field length can be obtained, with relatively low values of T/W and relatively high values of W/S, provided that sufficiently high values of take-off lift coefficient can be obtained. Therefore, the successful application of powered-lift concepts, which yield improved low-speed performance, will allow acceptable take-off field lengths to be obtained with values of T/W and W/S sized to obtain optimum cruise efficiency.

POWERED-LIFT CONCEPTS INVESTIGATED

The powered-lift concepts considered herein are described and discussed individually. Although the details differ, the fundamental consideration is the same for both subsonic and supersonic cruise vehicles; namely, to allow the wing area and installed thrust to be sized to provide optimum cruise efficiency while using powered-lift concepts to meet the low-speed operational requirements associated with conventional aircraft.

One particularly promising powered-lift concept, which may have near-term applications for long-haul subsonic transports, is over-the-wing blowing (OTWB). Figure 3 shows a photograph and a sketch of the concept applied to a subsonic transport configuration with an aspect-ratio-7.48 wing and a leading-edge sweep of 33.6°. The configuration is equipped with four, pylon-mounted, upper-surface engines with deflectable exhaust nozzles. Reference 2, which combined the analytical results of reference 3 and the experimental results of references 4 and 5, has shown that the OTWB concept with undeflected exhaust nozzles can provide substantial reductions in induced drag. The reduction in induced drag is provided by the jet exhaust which induces an upwash on the wing. The upwash rotates the wing force vector forward and effectively produces a negative increment in induced drag. Therefore, if it is possible to produce additional circulation lift by deflection of the exhaust flow downward onto the wing surface during take-off and landing, such an arrangement would provide not only improved low-speed performance but also improved cruise performance.

As was mentioned previously, powered-lift concepts have also been applied to supersonic cruise vehicles. Figure 4 shows a photograph of a large-scale advanced supersonic cruise arrow-wing configuration which has an aspect ratio of 1.72 and an inboard leading-edge sweep of 74°. The powered-lift concepts investigated for improved low-speed performance of this configuration are also sketched in figure 4 and include (1) boundary-layer control (BLC) for enhanced flap effectiveness and prevention of flow separation at high flap deflections, (2) OTWB for additional circulation lift (this concept also has another advantage in that the trailing-edge flap system may be continuous, rather than the segmented system necessitated by the use of the conventional underslung engines), and (3) thrust vectoring which provides increased lift by a combination of the direct vector component of thrust and by the additional circulation lift produced by flow entrainment.

LIFT CHARACTERISTICS

Subsonic Cruise Vehicles

Figure 5 shows the variation of additional circulation lift $C_{L,\Gamma}$, obtained with the OTWB concept, as a function of the ratio of the height of the engine above the wing to the engine diameter h/D. The data are presented for $\alpha = 0^\circ$ and $\delta_f = 45^\circ$. It should be noted that the exit nozzle deflection varied with h/D so that the jet would impinge at approximately the same chordwise location. From figure 5 it is seen that, as with other powered-lift concepts, relatively small values of thrust coefficient C_μ result in significant levels of additional circulation lift and that further increases in C_μ result in more gradual increases in $C_{L,\Gamma}$. Furthermore, from figure 5 it can be seen that there is only a slight increase in $C_{L,\Gamma}$ as h/D is increased from 0.5 to 1.0.

Figure 6 presents a comparison of the lift characteristics obtained for the OTWB concept with those for an upper-surface blowing (USB) concept applied to a configuration comparable with that used in the OTWB investigation (see ref. 6). The USB concept used rectangular exhaust nozzles having as aspect ratio of 6. On the basis of a comparison of the data for the OTWB and USB concepts, it would appear that both concepts produce essentially the same level of additional circulation lift. However, the reduction in induced drag provided by the OTWB concept in the cruise configuration indicates that such a configuration may have a higher level of cruise efficiency than a configuration with the USB concept.

In light of these considerations, the NASA Langley Research Center will be conducting tests with a large-scale model of the advanced OTWB subsonic transport configuration shown in figure 7. The configuration uses a supercritical airfoil with an aspect-ratio-12 wing and is designed for efficient cruise at Mach numbers of about 0.8. During the take-off and landing phases of flight, the exhaust is deflected downward onto the wing surface to provide the desired high lift for improved low-speed performance.

Supersonic Cruise Vehicles

Figure 8 summarizes the improvements in lift obtained with the various powered-lift concepts investigated for the advanced supersonic cruise vehicle. From figure 8 it is seen that the increment in lift provided by the plain trailing-edge flap is reduced for flap deflections above 20°, as a result of flow separation at the higher flap deflections. As would be expected, the application of BLC provides enhanced flap effectiveness and eliminates flap stall for flap deflections up to 40°. Figure 8 also shows that thrust vectoring provides an additional increment in lift; however, this increment was limited to the vector component of thrust. The fact that thrust vectoring failed to provide additional circulation lift is attributed to the relatively far aft position of the exhaust nozzles for the particular engine location considered. The data show further that the OTWB concept provides substantial additional increases in lift. This result is attributed to the continuous trailing-edge flap system, permitted by the upper-surface-mounted engines, and the additional circulation lift produced by the concept.

The potential benefits obtainable from the application of powered-lift concepts to the supersonic cruise vehicle are illustrated in figure 9. The relatively low value of lift curve slope, associated with the low-aspect-ratio, highly swept, arrow wing, and the tail scrape angle are seen to constrain the take-off lift coefficient of the basic concept to values of only about 0.55. Furthermore, the relatively high angle of attack associated with this lift coefficient results in substantial drag which penalizes the low-speed performance. In addition, the relatively high rotation angle requires the use of a visor nose for acceptable pilot visibility and also requires an elongated landing gear installation which results in a weight and volume penalty.

Results of airframe-engine sizing studies have indicated that significant improvements in supersonic cruise efficiency and range can be obtained by reducing the wing size of this configuration by about 25 percent. Therefore, to obtain acceptable take-off field lengths, the resized vehicle would require approximately a 25-percent increase in lift coefficient, which corresponds to $C_L \approx 0.7$.

Figure 9 shows that thrust vectoring in combination with BLC provides the desired lift coefficient of 0.7 at $\alpha \approx 6^{\circ}$, whereas OTWB and BLC provides a lift coefficient of 0.7 at $\alpha \approx 1.5^{\circ}$. The use of OTWB or thrust vectoring therefore permits operation at reduced angle of attack which would result in a significant reduction in drag and thereby provide improved low-speed performance. Furthermore, the reduced angle of attack would allow a reduction in landing gear length and may also eliminate the requirement for a visor nose, both representing a significant weight savings. However, the most significant point is that with the increased value of lift, the wing size can be reduced toward the optimum size for increased supersonic range while maintaining acceptable take-off and landing performance.

It should be noted that the OTWB concept appears to provide better low-speed performance than the particular thrust vectoring concept investigated. However, it is considered that, through proper design, the thrust vectoring concept might be as efficient as the OTWB concept and that the thrust vectoring concept may offer some advantages over other high-lift concepts for achieving improved lateral control. For example, one promising thrust vectoring concept which uses a two-dimensional exit nozzle design is illustrated in figure 10. Such an arrangement should provide improved powered-lift characteristics and also allow significant, and needed, improvements in roll control by the introduction of differential thrust vectoring.

LONGITUDINAL TRIM

It should be noted that the data presented in the previous section correspond to untrimmed values of lift coefficient, and that extremely large nose-down pitching moments accompany the increases in lift provided by the powered-lift concepts. The problem of providing pitch trim for subsonic transport configurations has been discussed in reference 7; therefore, the present discussion is limited to the problem of providing pitch trim for supersonic cruise vehicles.

Figure 11 shows the pitching moments produced by application of powered-lift concepts to the supersonic cruise vehicle. Relative merits of various means for providing pitch trim have been investigated for this configuration and the results are presented in figure 12. The analysis was conducted for a trim lift coefficient of 0.7 and a static margin $\left(dC_m/dC_L\right)$ of 3 percent. As would be expected, the use of a conventional aft tail for trim requires a download, whereas the canard concepts require an upload. Furthermore, both the conventional aft tail and the fixed canard require relatively high values of tail lift coefficient $\left(C_{L,tail}\right)$ and would therefore probably require a sophisticated high-lift system.

It is possible to achieve the favorable upload of the canard and to eliminate the requirement for a high tail lift coefficient by introducing a gearing arrangement which provides artificial stability by driving the canard surface so that the canard angle of attack is reduced as the aircraft angle of attack is increased. It should be pointed out that the geared canard requires the lowest lift coefficient per tail area ratio $\left(S_t/S\right)$ and may not require the sophisticated high-lift devices which would be associated with either the fixed canard or the conventional aft tail.

CONCLUDING REMARKS

The application of powered-lift concepts to advanced long-range subsonic and supersonic cruise vehicles appears promising for providing significant improvements in low-speed performance. The increased lift provided by the powered-lift concepts allows a reduction in both wing size and installed thrust requirements which yields a better engine-airframe match for improved cruise efficiency and range. The powered-lift benefits appear to be particularly significant for the supersonic cruise vehicle because of the inherently poor low-speed lift characteristics associated with the low-aspect-ratio, highly swept wing required for supersonic flight.

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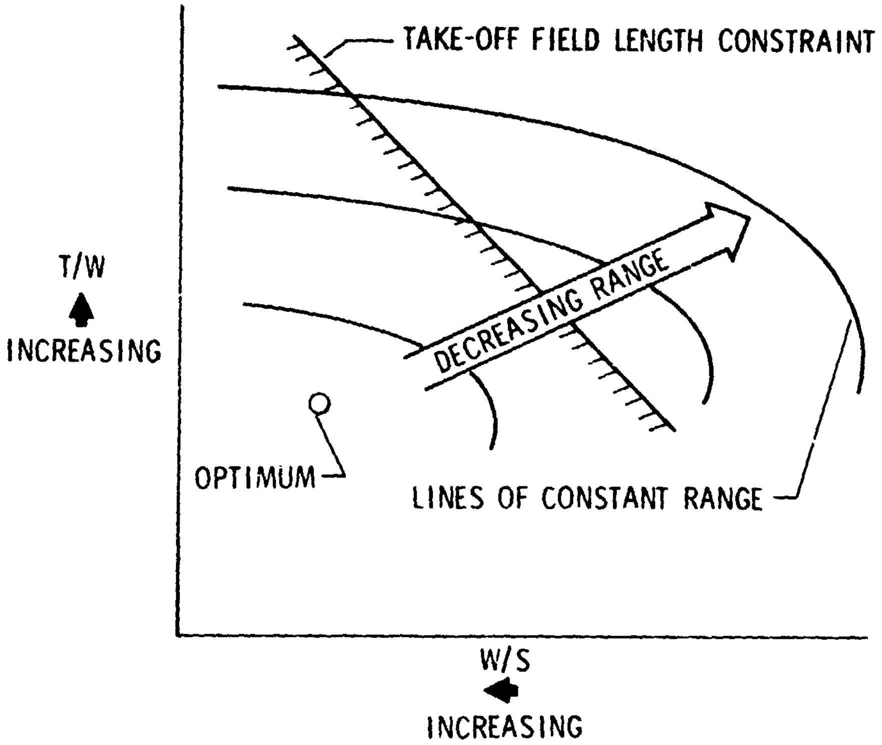

Figure 1.- Variation of range with T/W and W/S.

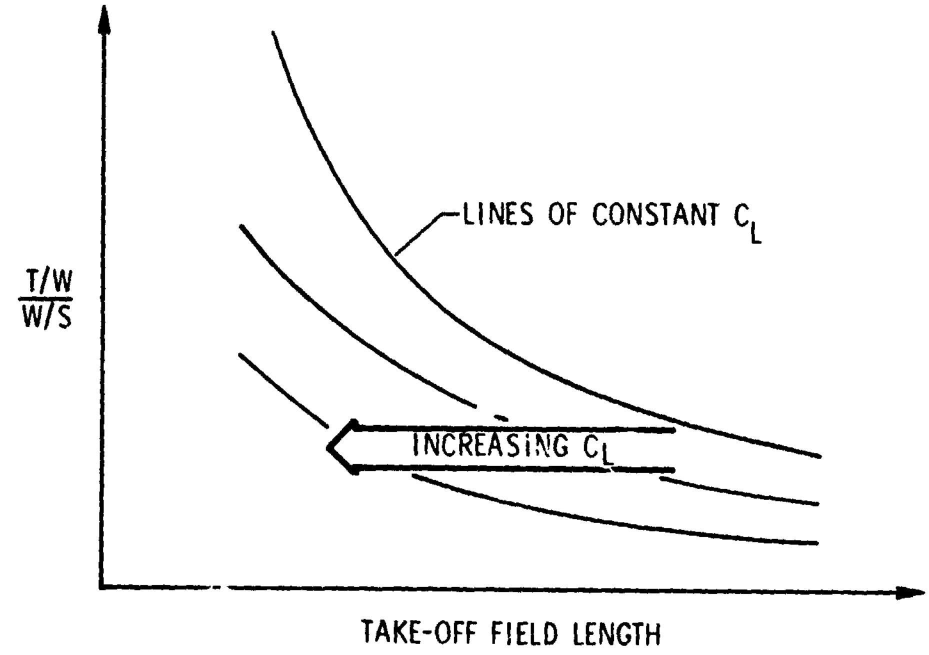

Figure 2.- Influence of C_L on take-off field length.

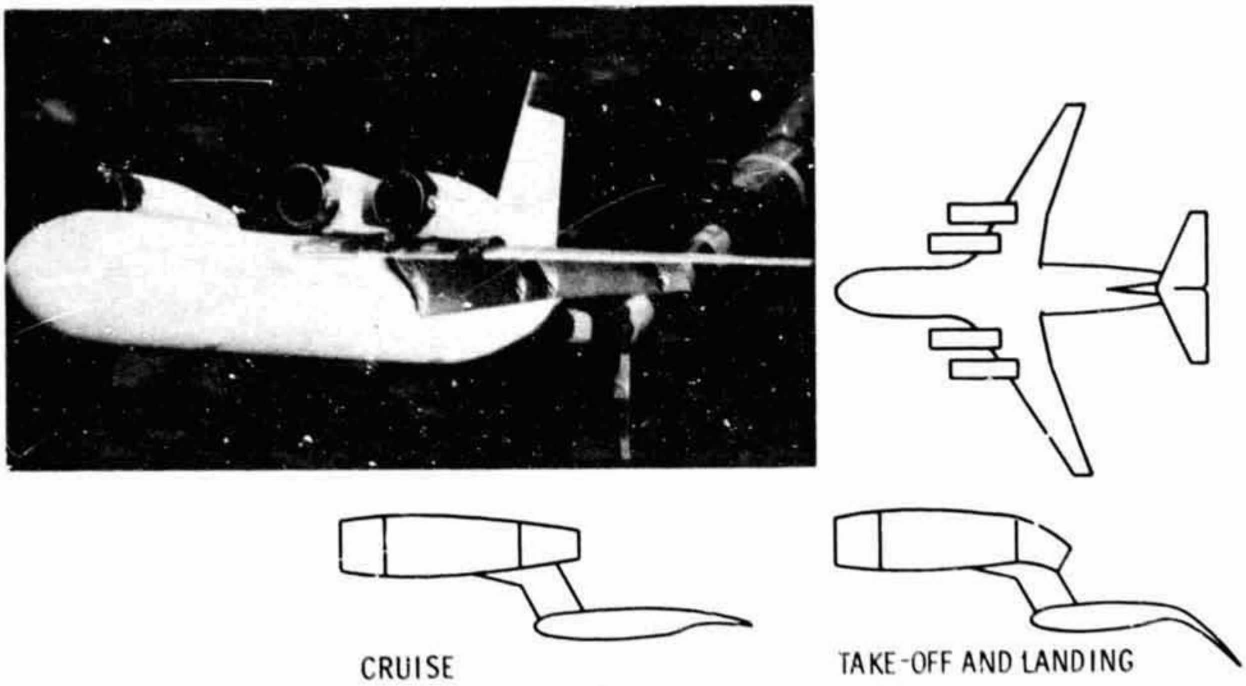

Figure 3.- OTWB concept applied to subsonic transport.

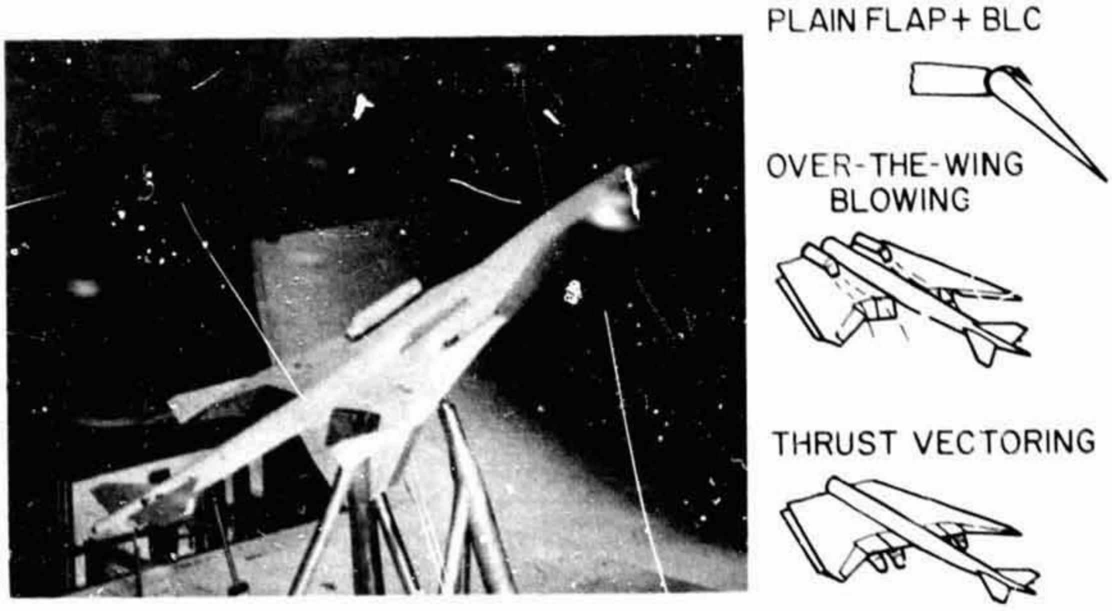

Figure 4.- Powered-lift concepts investigated for supersonic cruise configuration.

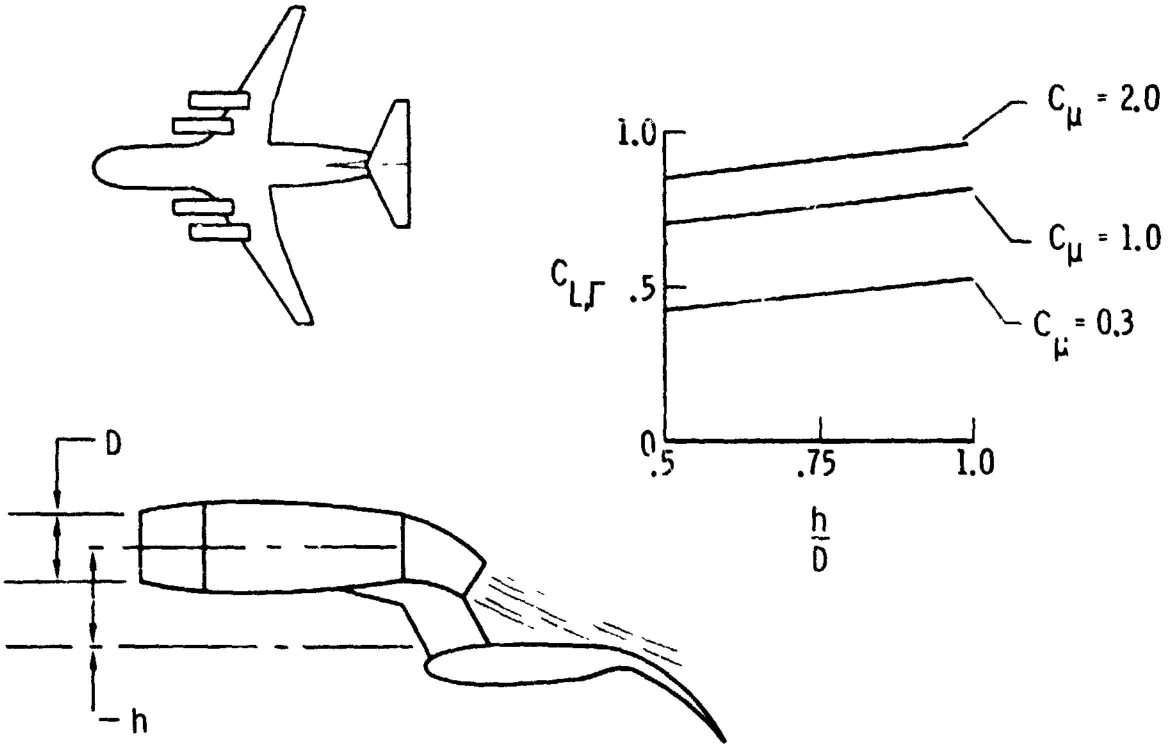

Figure 5.- Additional circulation lift produced by OTWB for subsonic cruise configuration. δ_f = 45°.

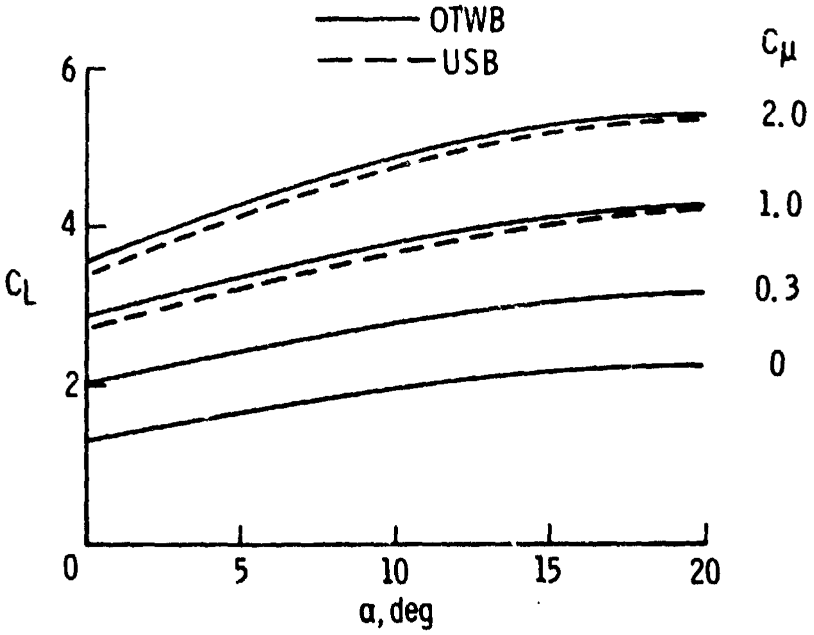

Figure 6.- Comparison of low-speed lift characteristics for OTWB and USB concepts applied to subsonic cruise configurations.

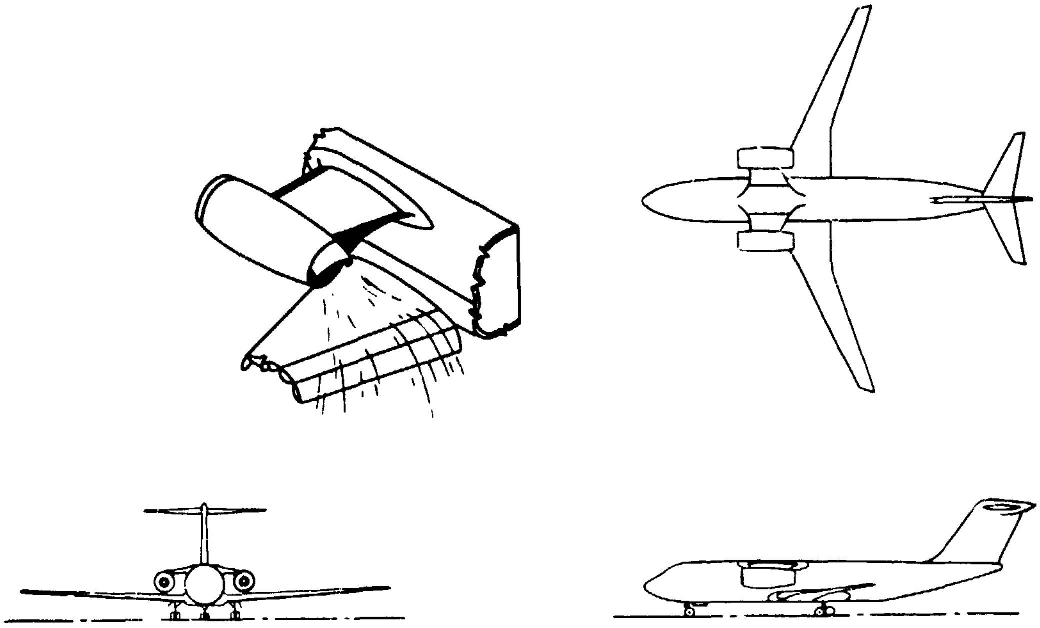

Figure 7.- Sketch of advanced long-haul subsonic transport with OTWB.

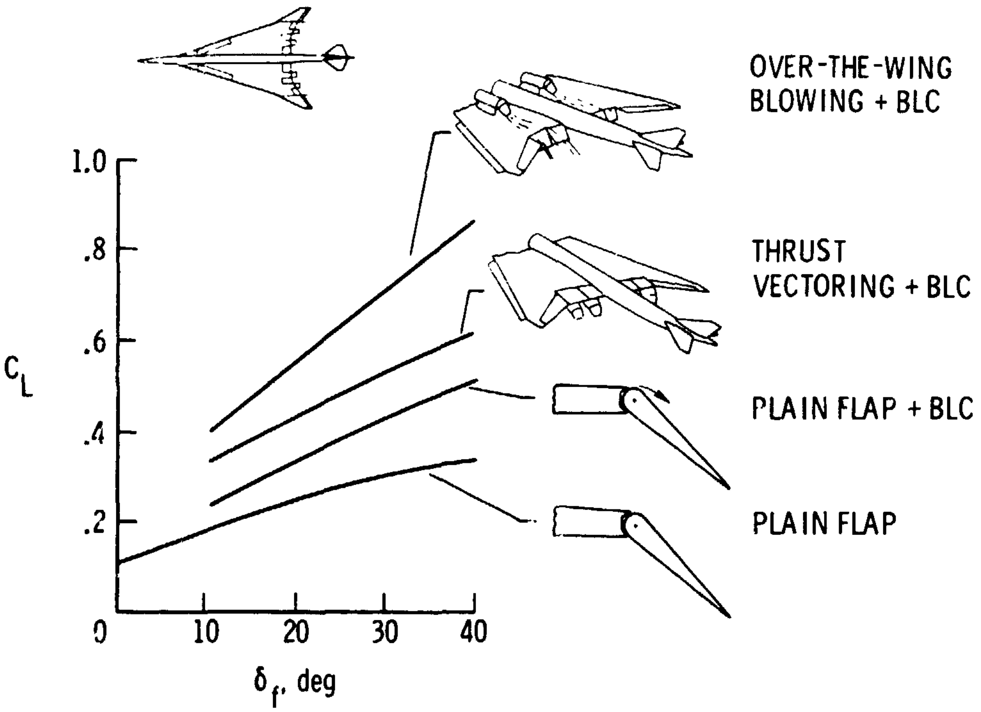

Figure 8.- Lift improvements due to powered-lift concepts for advanced supersonic cruise vehicle. $\alpha = 0^{\circ}$.

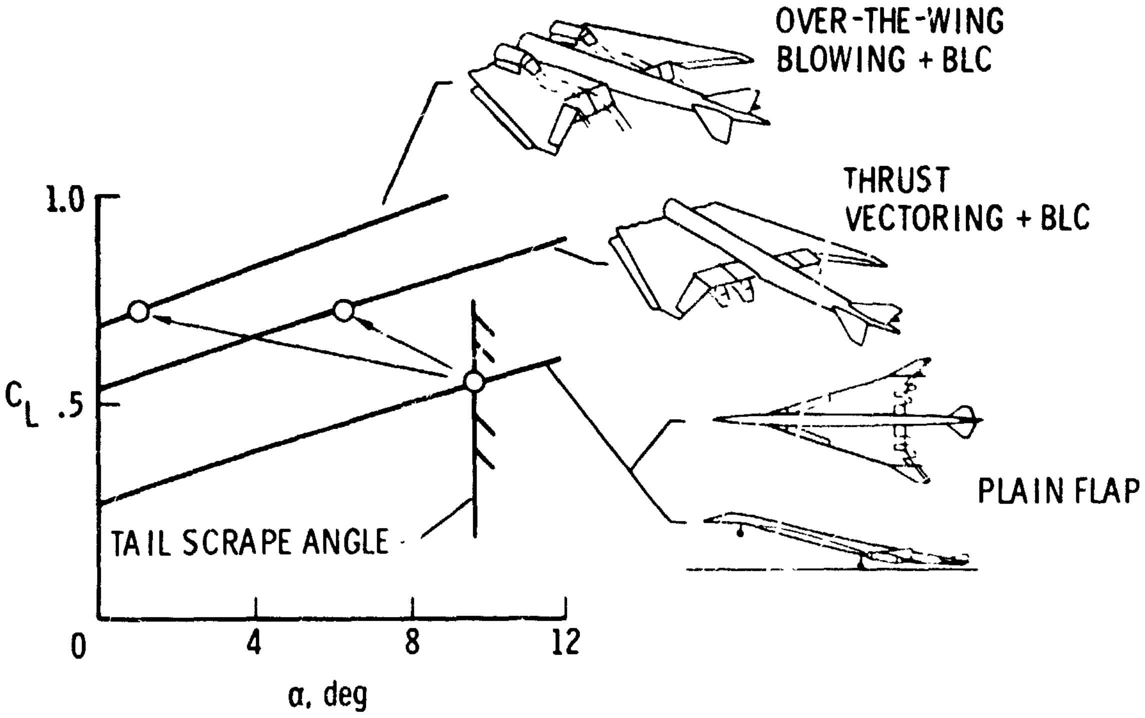

Figure 9.- Potential benefit of application of powered-lift concepts to supersonic cruise vehicle. $\delta_f = 30^\circ$.

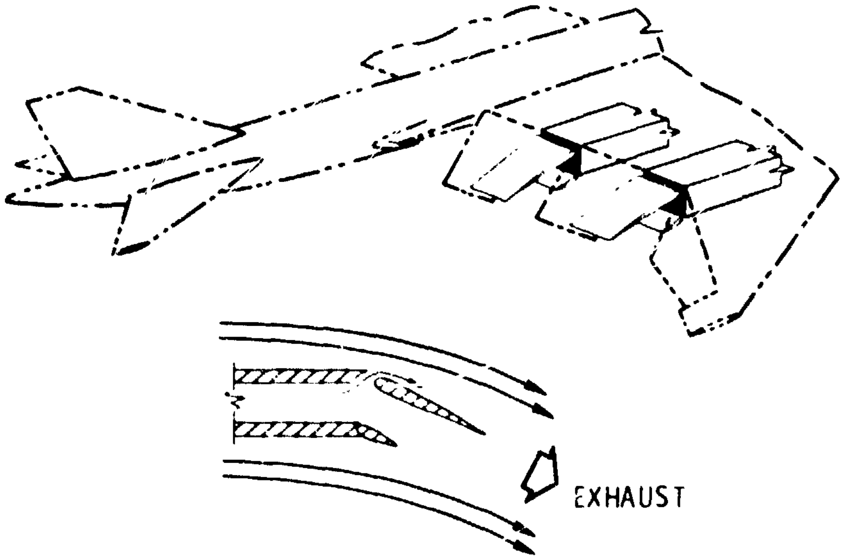

Figure 10.- Sketch of revised thrust vectoring concept for supersonic cruise vehicle.

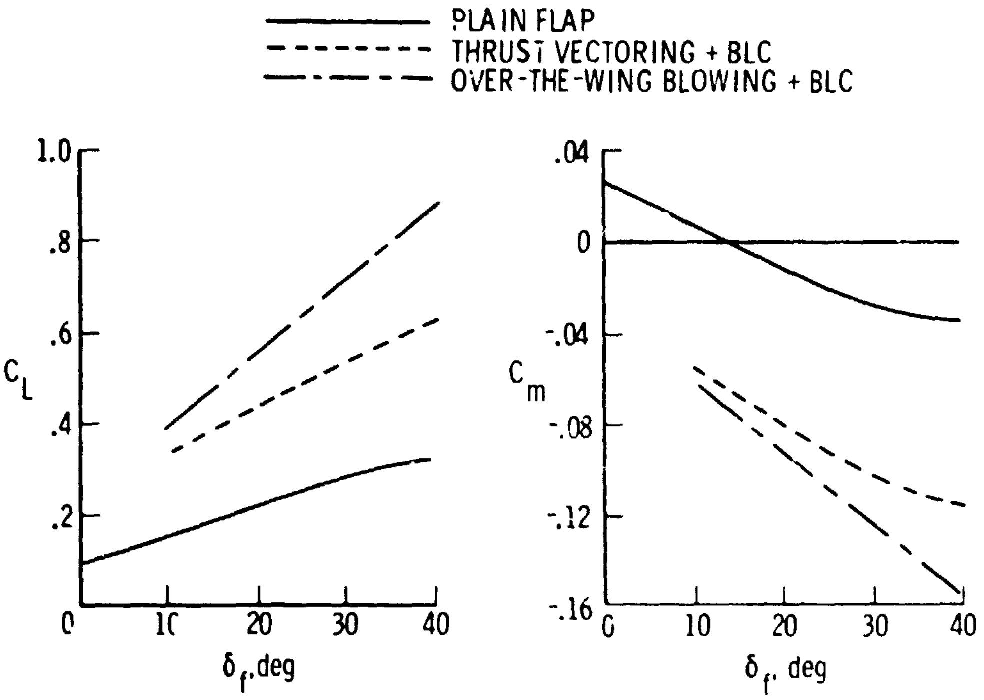

Figure 11.- Pitching moments introduced by application of powered-lift concepts to supersonic cruise vehicle. $\alpha = 0^\circ$.

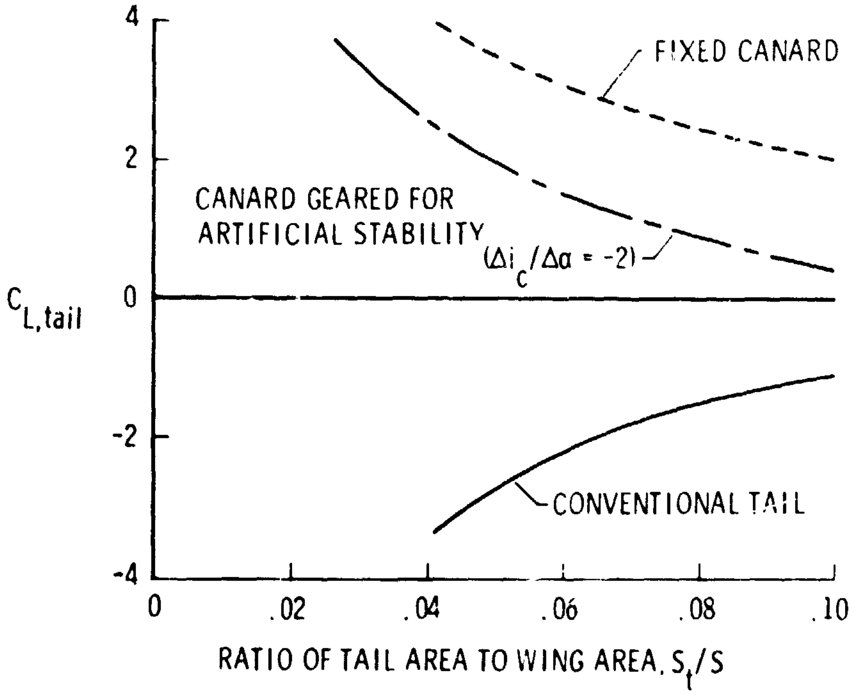

Figure 12.- Tail requirements to trim supersonic cruise vehicle. $C_L = 0.7$; 3-percent static margin.