Lift Fan V/STOL Concept for Future Applications

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The lift fan concept encompasses basically a V/STOL propulsion system consisting of a high bypass ratio jet engine. Jet engine thrust is installed in the aircraft for conventional flight, and this thrust is utilized as an energy source. Lift fans are sized for VTOL. Studies indicate that low aspect ratio wings suitable for fan installations compare very well with variable-geometry winged aircraft from a mission standpoint. In addition, vertifan aircraft can achieve V/STOL at nearly the cost of STOL only. Vertifan aircraft powered by lift fan propulsion systems are equally applicable to high subsonic or supersonic applications.

Nomenclature

AR = aspect ratio
c = airfoil chord length
C_D = coefficient of drag
C_{D_i} = coefficient of induced drag
C_{D_0} = coefficient of "zero-lift" drag
C_L = coefficient of lift
C_m = coefficient of moment
e = aircraft efficiency factor
GW = gross weight
KE = kinetic energy
L = lift
L/D = lift/drag ratio
M = Mach number
M_{DD} = divergence mach number
R = range
S = wing area
ΔS = "glove" area of a variable geometry wing
SFC = specific fuel consumption
T = thrust
t = airfoil thickness
t/c = airfoil thickness ratio
T/W = aircraft takeoff thrust/takeoff weight ratio
V = velocity
V_t = true velocity
W = weight
W/S = wing loading
W/W_0 = aircraft weight ratio (initial weight/initial weight weight less fuel weight)
Δ = value difference
$\delta \cdot_f$ = flap deflection
μ = coefficient of ground friction, or blowing momentum coefficient
ω = mass flow

Subscripts

A/B = after burner
A/C = aircraft
CR = cruise
LF = lift fan
VG = variable geometry

Concept Background

THE lift fan concept encompasses basically a V/STOL propulsion system consisting of a high bypass ratio jet engine. In fact, instead of simply augmenting the thrust of the basic jet engine, the jet engine is used primarily to power the bypass fan. By this method, augmentation of 200% to more than 400% of the static jet engine thrust can be achieved for vertical takeoff and hovering. To the V/STOL design engineer, the opportunity to augment the installed thrust for vertical takeoff and hover without the penalties of undue complexity, high cost, and excessive fuel consumption is indeed significant.

Components of the lift fan propulsion system, pioneered by the General Electric Company, are illustrated in Fig. 1. These components consist of the jet engine "*A*" connected to a diverter valve "*B*" and scroll "*C*" as well as fan "*D*," tailpipe "*E*," fan cover door "*F*," and exit louvers "*G*." In hover operation, the engine exhaust travels through the diverter valve and scroll, and impinges on turbine blades located around the periphery of the fan, thereby turning the fan, which is located in the chord plane of the wing. With the fan cover doors and exit louvers open, the air is directed vertically downward producing lift. For transition, the exit louvers direct the slipstream rearward for forward acceleration. After the aircraft has passed its conventional stall speed, the diverter valve directs the exhaust out of the tailpipe, the fan inlet doors and exit louvers close, and the aircraft flies as a conventional jet aircraft from then on. The procedure is reversed for a vertical landing.

The lift fan concept occupies a unique position within the V/STOL aircraft spectrum, because it is the only system that is associated with the high speeds of conventional jet aircraft in forward flight, while maintaining a hovering efficiency nearly equal to other large rotor craft, such as propeller V/STOL aircraft.

Installed Thrust

Thrust required for jet aircraft with varying applications and performance levels based on the state of the art of aircraft flying today is shown in Fig. 2.

To design any equivalent high-performance V/STOL aircraft, either lift must be installed to equal gross weight of the

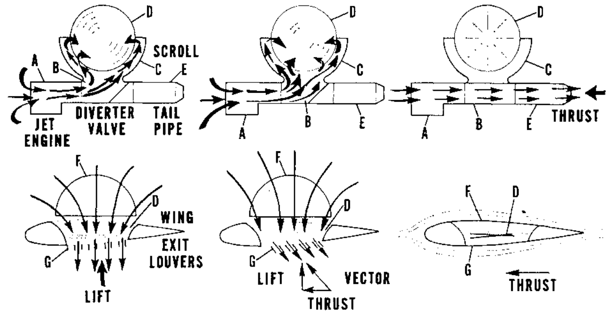

Fig. 1 Lift fan concept.

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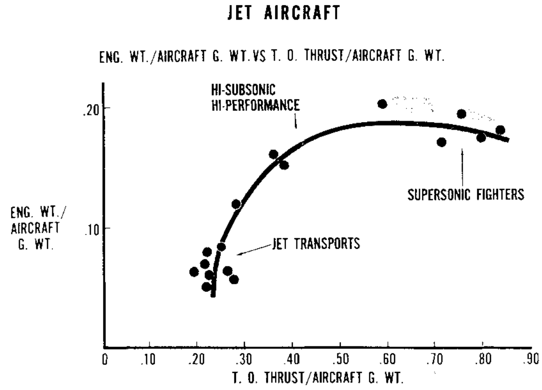

Fig. 2 Cruise thrust required.

aircraft in addition to the basic jet engine cruise thrust required, or the installed jet engine thrust must in some way be augmented. It is usually agreed that the augmentation method is superior because of the lower value of total installed power. This can be accomplished in many ways, such as using the same engine for lift and cruise, or using the cruise engine also for lift in addition to augmentation such as aspiration, separate lift jet engines, fans, etc.

Based on Fig. 2, the lift fan V/STOL concept shows excellent applicability toward subsonic applications, since the basic required installed thrust for subsonic aircraft always has a value that is equivalent to a small percentage of the vehicle's gross weight. By installing only this small amount of jet engine thrust and sizing fans for VTOL, considerable savings are realized in terms of engine size, cost, fuel consumption, and associated logistics.

The basic principle on which the lift fan concept is founded is as follows: for a jet powered V/STOL aircraft, only that amount of jet engine thrust required for conventional flight is installed, and the fans, using the installed jet engine thrust as a basic power source, are sized to produce lift in excess of the aircraft's gross weight.

Comparison with Variable Sweep

The current tactical fighter experimental development program, based on the variable-geometry-STOL-only concept, represents probably the most up to date aircraft design technology. Figure 3 illustrates the basic advantages of the variable geometry concept whereby low wing loadings, high C_L's, and aspect ratios are available for short field takeoffs and landings; matched sweep and high L/D's are available for long range subsonic cruise, and low aspect ratio and thin wing thickness ratios are available for low-altitude supersonic flight. It is of interest to compare lift fan V/STOL design concepts with variable geometry as a measure of its applicability toward supersonic use.

Figure 4 illustrates the major design problem associated with the lift fan concept. Basically, the lift fan concept requires that fans be buried in the fuselage, in the wing, or in both for vertical takeoff. Generally speaking, fans will be buried within the wing for most designs. This requires that the wing house the fan with a suitable airfoil and wing thickness. If a short chord is used, the thickness ratio is high. To reduce thickness ratio, chord length can be increased. The primary problem then is to match aircraft aerodynamics to a wing with a large chord. This will ordinarily result in a low aspect ratio wing.

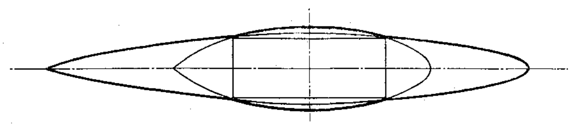

Fig. 4 t/c vs fan case.

In considering divergence Mach number, a review of wind-tunnel data (Fig. 5) indicates that, below an aspect ratio of 1.5, there is little difference in divergence Mach number regardless of thickness ratio. Figure 6 indicates that above Mach 1.4 there is little difference in optimum L/D regardless of aspect ratio. From a supersonic consideration, low aspect ratio wings are advantageous because of better weight characteristics, particularly since an L/D penalty is not a critical consideration.

Figure 7, based on empirical data, illustrates the fact that, the higher the wing loading, the lower the total aircraft structural weight as a function of gross weight. This indicates that another desirable low-altitude supersonic design consideration is to maintain high wing loadings.

Figure 8 indicates that, although all aircraft flying today have optimum supersonic L/D's of approximately 3.5, current technology indicates that L/D's of 6 or 7 at Mach 3.0 are obtainable with properly designed aircraft. This consideration alone has far-reaching implications in terms of thrust required for supersonic flight.

Figure 9, based on empirical data, indicates that by proper adjustment of wing area and total aircraft wetted area a very low value of C_{D0} (basic aircraft zero lift drag) can be obtained.

If proper attention is given to obtaining a low C_{D0}, respectable nautical miles per pound of fuel (for subsonic cruise) can still be obtained with low aspect ratio wings due to characteristics shown in Fig. 10 where the efficiency factor (e) in the denominator of the C_{D_i} expression is nearly 1.0 at an aspect ratio of 1.0 to 1.5, as compared to an industry average of approximately 0.8 for aspect ratios of 2.5 and above.

Preliminary designs of lift fan aircraft, as shown in Fig. 11, and based on Figs. 4–10, have shown the feasibility of providing respectable subsonic cruise characteristics such as shown in Fig. 12, where both the optimum L/D (for maximum endurance) and $V_t L/D$ (for maximum nautical miles per pound of fuel) peaked at the aircraft's divergence Mach number at its best subsonic cruise altitude. Furthermore, the aircraft illustrated in Fig. 11 has an average of 4% wing thickness ratio with a speed capability of Mach 1.2 at sea level and in excess of Mach 2.5 at altitude.

In comparing this to a variable geometry design for subsonic cruise, Fig. 13 illustrates that the lift fan design with a low aspect ratio wing could obtain an $L/D_{\text{opt cruise}}$ of 8 at a

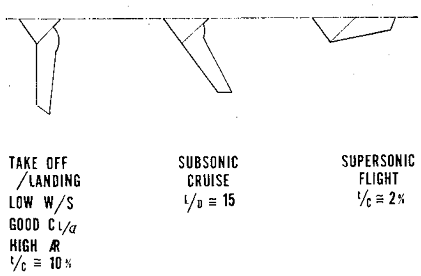

Fig. 3 Variable sweep, matched system.

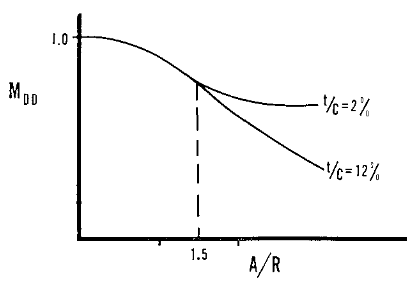

Fig. 5 Divergence Mach number.

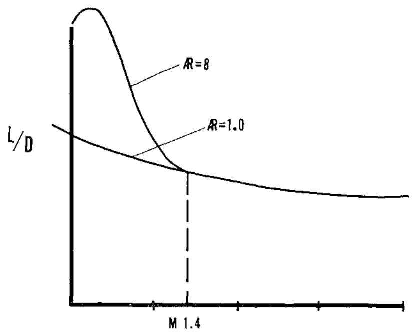

Fig. 6 Lift/drag.

Mach number of 0.92, whereas the variable geometry design could achieve an $L/D_{\text{opt cruise}}$ of 15 at a Mach number of 0.7. In the Breguet range equation,

$$R = [(V_t L/D)/SFC][\log_e(W/W_0)]$$

utilizing $V_t L/D$ as a range parameter, the variable geometry design has a value of 10.5, whereas the lift fan has a value of 7.36. This would indicate a marked superiority for the variable geometry design; however, consideration must now be given to weight penalties associated with each concept.

Figure 14 illustrates the results of prior studies[1] of wing weight penalties associated with the lift fan concept requiring large cutouts in a wing. Basically these studies showed that, with a single cutout, the wing weight penalty, as compared to an equivalent wing without a cutout, varied from (in essence) zero penalty at a wing aspect ratio of 1.0 to approximately a 40% penalty with a wing aspect ratio of 10. Therefore, with a wing such as utilized on the aircraft of Fig. 11, little if any penalty would result.

Conversely, a wing weight penalty[2] of a variable geometry wing can be defined as follows:

$$WT_{VG} = WT_{\text{basic}}[1.16 + (S/S)]$$

where WT_{VG} is the total wing WT and WT_{basic} would be the calculated weight of an equivalent wing without variable sweep. (Note that the WT_{basic} would be computed for the equivalent wing based on the unswept or most area of the variable geometry wing.) Therefore, the weight penalty would include 16% for the hinge mechanism, plus a factor based on ΔS, the glove area, to S the total wing area.

In addition, Fig. 7 showed the results of tabulating empirical data with respect to total structural weight as a function of wing loading. If the lift fan design has been optimized for the highest wing loading possible with an associated low total structural weight, the variable geometry wing will have a much lower wing loading (based on the unswept position), and therefore a higher total aircraft structural weight can be expected.

Referring to the $V_t L/D$ range factor comparison, where the lift fan factor of 7.36 is only 70% of the variable geometry factor of 10.5, if fuel equivalent to the variable geometry weight penalties as shown in Fig. 15 were added to the lift fan's fuel capacity, it can be expected that little difference would exist between the two examples with respect to combat radius.

Finally, with respect to supersonic drag, Fig. 16 shows the results of wind-tunnel tests of "gothic" wing planforms (particularly suitable to lift fan aircraft designs) where, with a 1% wing thickness there is no drag rise at Mach 1.0, and very little drag rise at a 4% thickness. When an optimized fuselage is utilized in conjunction with the "gothic" planform, the resultant "fixed" configuration could be expected to have not only a small drag rise, but a relatively low supersonic drag as well.

In continuation of the comparison between the lift fan and the variable geometry supersonic designs, Fig. 9 indicated that very low C_{D_0}'s can be obtained with a fixed value of the parameter $2S/S_{\text{wet}_{A/C}}$. This can be accomplished with the lift fan because of its resultant fixed geometry. With respect to a variable geometry design, a compromise is much more likely to occur, as shown in Fig. 17, because of the great difference in projected wing area between the swept and unswept wing positions. Actually the highest C_{D_0} value is very likely to occur with the wing in the swept position as a result of the value of "2S" with the wing swept, being the lower value, and therefore the total value of the parameter $2S/S_{\text{wet }A/C}$ being lower with the resultant higher C_{D_0} under these conditions.

Considering coefficient of drag vs Mach number, Fig. 18 compares the discussed lift fan and variable geometry designs. As discussed previously, the C_{D_0} of the variable geometry wing is likely to be higher, and it would carry through the drag rise into the supersonic regime. If for equivalent designs this

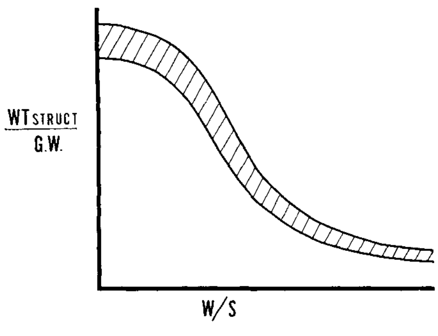

Fig. 7 Structural weight.

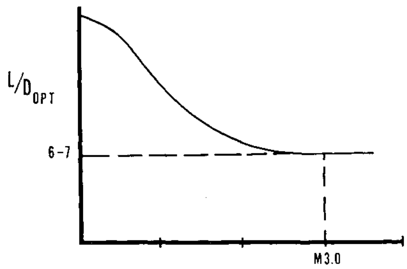

Fig. 8 L/D opt cruise.

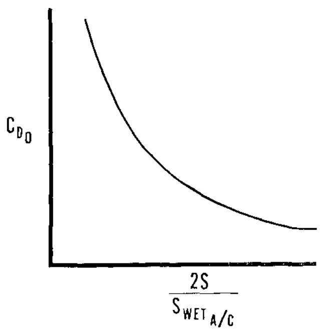

Fig. 9 Zero lift drag.

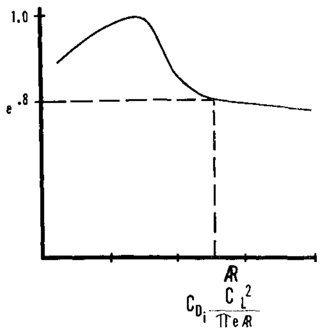

Fig. 10 Induced drag.

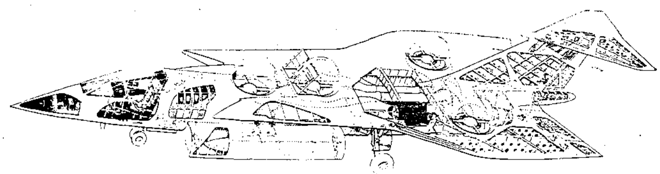

Fig. 11 Mach 2 lift fan aircraft.

holds true, then for a given supersonic acceleration less thrust would be required for the lift fan design than for the variable geometry design.

A subject not considered so far in this hypothetical comparison is weight of propulsion systems. Assuming that the total propulsion system weight of the lift fan V/STOL aircraft would exceed the total propulsion system weight of the variable geometry STOL-only design, it should be recognized that the foregoing discussion has been based on comparison of design missions. Because of the excellent STOL characteristics of the lift fan design, the small additional propulsion system weight, if added on to the design VTOL gross weight value, would require only a fraction of the variable geometry STOL run for takeoff, and it would still retain the versatility of true VTOL when required.

When considering V/STOL designs only, Fig. 19 presents data on weight of V/STOL propulsion systems. Most competitive systems are quite close when little hover time is required. The lift fan concept shows a marked superiority when extended hover time is required. Furthermore, Fig. 19 utilizes a parameter of weight of propulsion system as a function of lift; however, a more accurate parameter would be weight of propulsion system to allowable VTOL gross weight. To arrive at meaningful data in this respect is a function of finite designs and the cleverness of the designers, since the major decrement to available lift (and therefore reduced gross

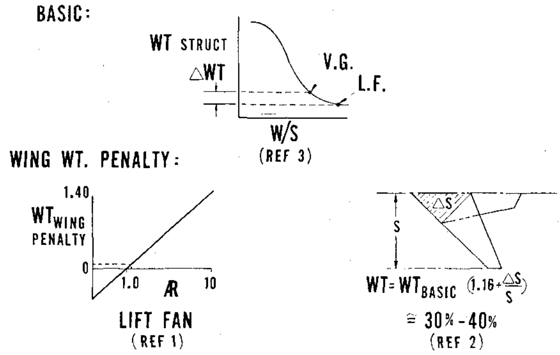

Fig. 15 Variable geometry vs lift fan weight.

weight) is due to control power requirements. Suffice it to state here that, with the lift fan, concept designs have been formulated whereby nearly all control is obtained with power transfer, thereby allowing a very minimum of lift reduction to establish design gross weight.

Finally, if V/STOL is desired, the lift fan concept, based on the foregoing discussion, seems applicable to supersonic designs as well as subsonic. Furthermore, in considering finite V/STOL mission design requirements, it would seem that the lift fan concept holds a clear edge over any system incorporating V/STOL propulsion systems in conjunction with variable geometry. This conclusion is arrived at as a function of Fig. 19, where even with a parameter of weight of propulsion system as a function of lift (not to mention weight of propulsion system to gross weight), the lift fan propulsion system is fully competitive with all other concepts. If then the weight penalties of variable geometry are added to the propulsion system penalties (as compared to conventional aircraft), it would seem that the lift fan concept holds a definite edge. If, when considering extreme ferry ranges, a variable geometry V/STOL design still seems desirable, consideration could then be given to disposable wing tips (for increased aspect ratio) added to the lift fan design, so as to retain the expected superior combat mission capability.

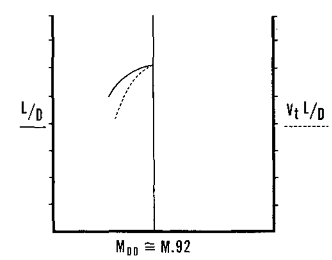

Fig. 12 Optimum subsonic cruise.

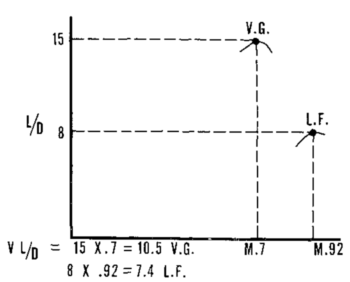

Fig. 13 Subsonic cruise.

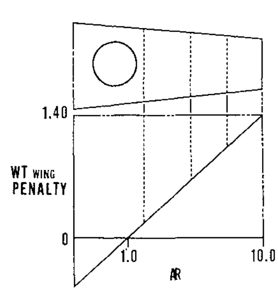

Fig. 14 Weight penalty.

Subsonic Aircraft

The lift fan V/STOL concept can compete favorably with STOL-only logistic aircraft. As shown in Fig. 20, the ability of any aircraft to achieve short takeoff and landing is a function of wing loading (W/S), thrust-to-weight ratio (T/W) and aspect ratio (AR) as related to maximum lift coefficient ($C_{L_{max}}$) obtainable. As shown in Fig. 21, the limits of $C_{L_{max}}$ which can be obtained with complex mechanical systems remain at about 2.5. For high gross weight aircraft, this is hardly significant in trying to obtain takeoff and landing runs of 1500 ft or less. To exceed a $C_{L_{max}}$ of 2.5, not only additional complex systems are required, but also greater installed power. In Fig. 21, the solid black lines represent aircraft with mechanical devices only (flaps, slats, etc.) to increase $C_{L_{max}}$. The solid black line representing a wing loading (W/S) of 100 approximates today's commercial jet transports. In this same figure, to reduce the takeoff distance to 1500 ft or less, an increase in aspect ratio (and preferably reduced wing

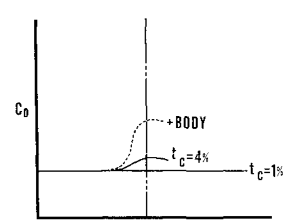

Fig. 16 Gothic wing.

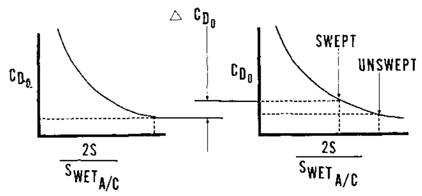

Fig. 17 Lift/fan vs variable geometry.

loading), thrust-to-weight ratios, and a high C_L system such as boundary-layer control is required. Under these conditions, the increased aspect ratio and/or wing area (reduced wing loading), increased thrust-to-weight ratio, and high C_L system represent increased weight and complexity.

Figure 22 shows a series of high-lift devices wherein C_L, over the basic airfoil, range as high as 14.7. One thing is common to all of these systems: as $C_{L_{max}}$ increases so does C_m; therefore control power requirements increase, resulting in oversized control surfaces and possibly even in reaction control. This is further illustrated by Fig. 23 wherein 100% design speed represents the minimum control velocity of a conventional design. If this speed is reduced by 50%, the control surfaces would have to increase by approximately 300 to 400%, or reaction control would have to be supplied.

Finally, for safety reasons, the STOL aircraft designer is forced into power-interconnect systems to eliminate catastrophic asymmetric loadings at very low velocities.

When all of the forementioned STOL criteria are compared to a lift fan V/STOL design (both being related to a conventional aircraft of equal performance), it can be shown that the penalties are nearly equal, but the flexibility of true VTOL remains with the lift fan design.

One area worthy of note is not necessarily limited to the lift fan, but it is of concern to all V/STOL designers. Historically, people have been prone to compare a given V/STOL aircraft to an equivalent conventional aircraft, and they have been quick to point out the reduced range/payload of the V/STOL aircraft as a result of the increased weight of its propulsion system. The normal and likely erroneous conclusion then follows that V/STOL is too expensive to consider for replacing conventional aircraft. A basic and obvious fact ignored with this type of logic is to ignore the extensive landing-field requirements of conventional jet aircraft. If the thousands of feet of hard surfaced runways (which implies the building material, construction equipment, the noncombative personnel and their supporting logistics, and vehicles to supply these items) are eliminated from the total weapon system logistic chain, the V/STOL weapon system could very well result in the cheapest total system. Of particular interest to the lift fan designer, regarding logistic support, is this concept's minimum ground erosion characteristics and related site preparation requirements.

Possible Applications

It should also be noted that the current status of this concept is merely on the threshold of development, and it can be compared to jet engines during the World War II time period. Although a considerable amount of data has been accumulated in recent years, culminating recently in the XV-5A (Fig. 24), current studies indicate that orders-of-magnitude increases, within the lift fan state of the art, can be expected with continued development. Some possible applications are illustrated in Figs. 25–28.

Figure 25 represents a 7000-lb VTOL, gross weight aircraft utilizing a single GE J85-13 coupled to three 36-in.-diam fans, with a wing thickness ratio of 10%. This provides a small, in-

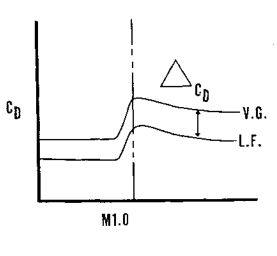

Fig. 18 Supersonic thrust required.

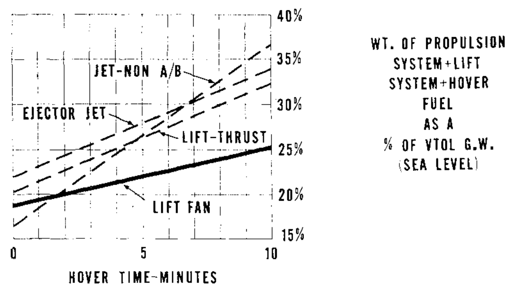

Fig. 19 Lift fan compared to high-performance V/STOL aircraft.

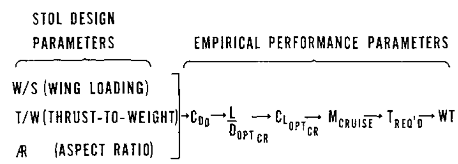

Fig. 20 STOL aircraft design.

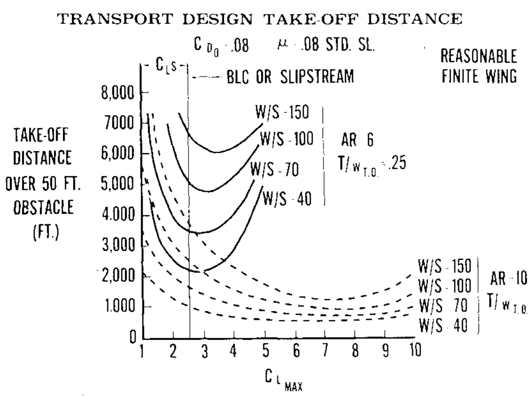

Fig. 21 Effects of W/S, T/W, and AR on STOL A/C design.

NO.	HIGH LIFT DEVICE	FLAP TYPE	$\delta°_{f\ opt}$	$\Delta C_{L_{MAX}}$	$\Delta C_{m_{c/4}}$	SYSTEM WT / WING AREA LBS./FT.^{2}
1		BASIC SECTION NACA 63-412	–	0 ($C_{L_{MAX}}$ = 1.3)	0 ($C_{m_{c/4}}$ -.3)	0
2		SPLIT	60	.8	-.25	0.35
3		PLAIN	32	1.0	-.28	0.7
4	(20% SLAT)	FOWLER	40	2.0 (2.6)	-.5 (-.35)	1.25 (1.43)
5	(20% SLAT)	SLOTTED FOWLER	50	2.2 (2.8)	-.56 (-.41)	1.3 (1.48)
6	(20% SLAT)	SINGLE SLOTTED	40	1.65 (2.25)	-.44 (-.29)	1.2 (1.38)
7	(20% SLAT)	DOUBLE SLOTTED	40/70	2.4 (3.0)	-.7 (-.55)	1.3 (1.48)
8		DOUBLE SLOTTED & DROOP NOSE	40/70	3.0	-.35	1.48
9		MODERATELY BLOWN (C_μ = .3)	53	4.6	-.7+	4
10		BLOWING & SUCKING SUP. CIRCUL. (C_μ=8)	75	14.7	-2.1	5.25
11		JET FLAP C_μ = 8	50	12	-5.7	5

ALL FLAPS 30% c, 100% b, STAND. ROUGHNESS, ZERO SWEEP, AR = 12
FOR X% SPAN MULTIPLY VALUES BY X% APPROX.
LIFT & MOMENT REDUCTION FACTORS: .9 (AR=6), .75 (AR=4), .52 (AR=2)
$C_{L_{MAX}}$ VALUES ARE FOR UNTRIMMED FLIGHT; $-\Delta C_{L_{MAX}}$ DUE TO TRIM = $C_{m_{c/4}} \frac{c}{l_t}$
$\frac{\text{SYSTEM WT}}{\text{GW}} = \frac{\text{SYSTEM WT}}{S_W} \times \frac{1}{(W/S)}$

Fig. 22 Characteristics of high-lift devices for STOL.

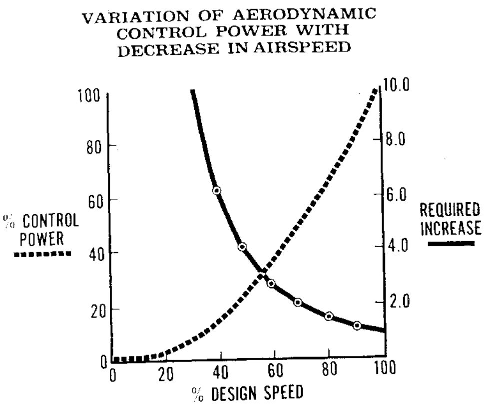

Fig. 23 Effects of STOL on control power.

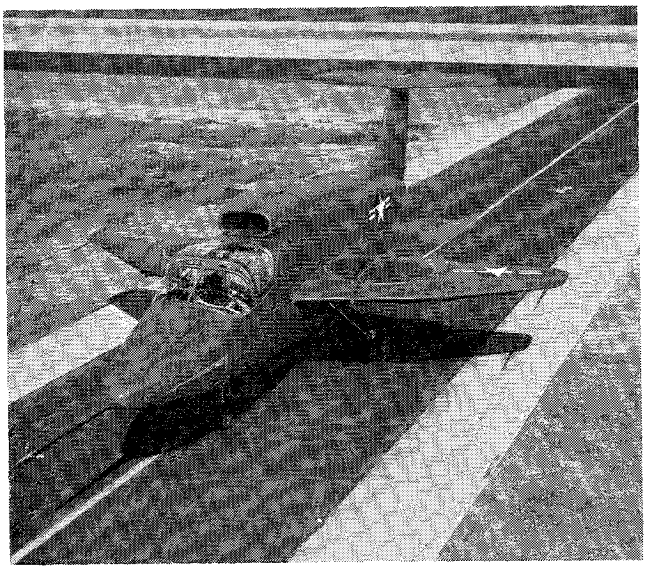

Fig. 24 XV-5A.

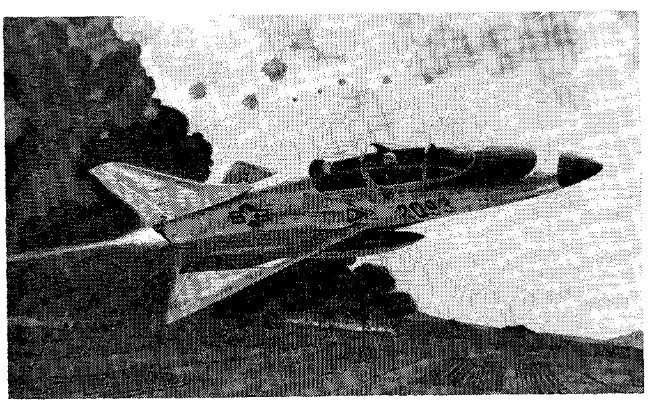

Fig. 25 COIN fighter.

expensive V/STOL aircraft designed to accomplish a counter-insurgence mission, while maintaining a Mach 0.9 capability at sea level.

Figure 26 illustrates a 15,600-lb gross weight aircraft utilizing two GE J85-13 engines coupled to three 50-in.-diam fans. It has a wing thickness ratio of 8%. Its divergence Mach number is 0.92, and it will fly up the drag rise in level flight to Mach 0.95. With a 50-fps vertical gust at Mach 0.9, the aircraft would pull less than 2*g*.

Figures 27 and 11 present a 27,000-lb gross weight design, utilizing two GE-1 engines and four-56-in.-diam fans. It has

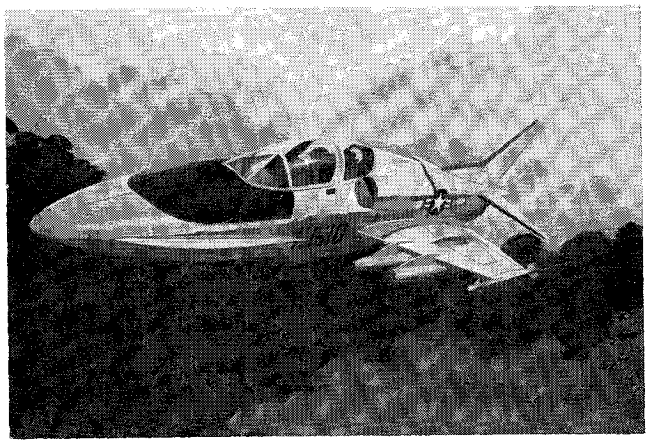

Fig. 26 Subsonic surveillance/attack.

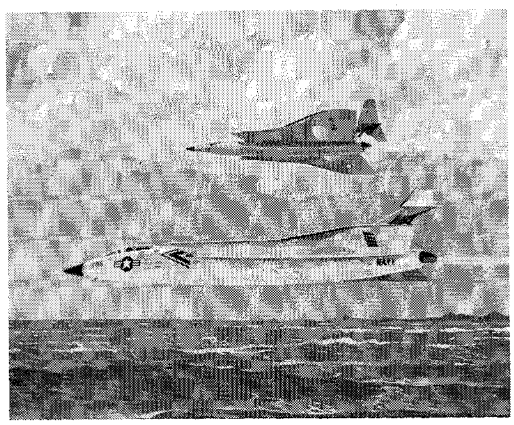

Fig. 27 Low-altitude supersonic attack.

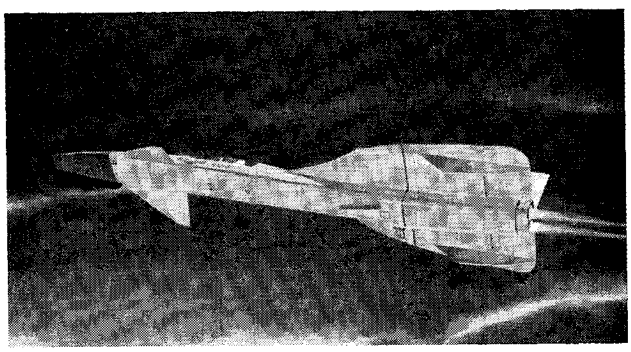

Fig. 28 Supersonic cruise interceptor.

an average wing thickness ratio of 4%, and it can accomplish Mach 1.2 at sea level and in excess of Mach 2.5 at altitude.

Figure 28 illustrates a 103,000-lb, Mach 3.2, 70,000-ft supersonic cruise design, utilizing two GE J93 engines. This design has a 3.7% wing thickness ratio, and utilizes four 7-ft-diam fans and one 9.5-ft-diam fan.

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