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THRUST AUGMENTOR APPLICATION FOR STOL AND V/STOL

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16. Abstract

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Abstract

A general parametric description is suggested for thrust augmentor application to STOL and V/STOL aircraft. The parameters and their relationships are discussed using several aircraft augmentor integration problems. For a STOL transport design, the ram drag is a key consideration, limiting the maximum gross augmentation that can be utilized. Maximizing gross augmentation and balancing the aircraft are key considerations for a V/STOL fighter design. Results from wind-tunnel investigations on several different thrust agumentor concepts and system studies on STOL transport designs form the basis for the discussion and conclusions in the paper.

Nomenclature

- A = area, m^2 (ft^2)
- C_L = lift coefficient, lift/$q_\infty S$
- h = nozzle height, m (ft)
- ℓ = shroud length, m (ft)
- m = mass flow, kg/sec (lbm/sec)
- p = nozzle pitch (distance between nozzles), m (ft)
- P = absolute pressure, N/m^2 (lb/ft^2)
- q = dynamic pressure, N/m^2 (lb/ft^2)
- S = wing area, m^2 (ft^2)
- t = nozzle gap width, m (ft)
- $\bar{t}$ = average nozzle gap width, m (ft)
- T = thrust, N (lb), or temperature, °K (°R)
- V = velocity, m/sec (ft/sec)
- θ_T = angle from design reference, deg

Subscripts

- a = actual
- d = duct
- e = shroud exit
- I = isentropic
- J = jet
- n = nozzle
- s = secondary
- t = shroud throat
- Γ = circulation
- ∞ = ambient

Introduction

The capabilities of the thrust augmentor have led to two proof-of-concept research aircraft. The first is the NASA Augmentor Wing Jet STOL Research Aircraft shown in Fig. 1. This aircraft, a modified De Havilland C-8A Buffalo, has about half its thrust in a wing trailing-edge augmentor and the other half, in rotating nozzles on the nacelles. It has been flight tested extensively since 1972. The second aircraft is a Navy-Rockwell International XFV-12A (Fig. 2). This V/STOL supersonic fighter has spanwise augmentors in the canard and wing and will first fly in 1978.

Even with these two aircraft and the research programs leading to their development, the technology base of thrust augmentor application is not extensive. Much of the information consists of empirical data from laboratory tests of idealized models, wind-tunnel tests of specific configurations, or theoretical performance based on inviscid analyses with empirical corrections.

Because of their large volume of internal and external mechanical devices and the high sensitivity of the mixing process to losses, the success of the thrust augmentor, more than most propulsive devices, depends almost totally on careful integration with the aircraft structural, aerodynamic, and control characteristics. To achieve this integration, a designer needs several tools:

(1) Parameters necessary to describe the augmentor and its performance

(2) Relationships between these parameters based on empirical or theoretical data

(3) Special considerations or limitations of specific concepts

The objectives of this paper are to

(1) Suggest a general, parametric description of thrust augmentor application to STOL and V/STOL

(2) Comment on the use of empirical and theoretical data

(3) Comment on general aircraft-augmentor integration problems

(4) Comment on key design considerations for specific application to STOL transports and V/STOL fighters.

Parametric Description

A parametric description should satisfy several criteria. It should be sufficient to describe the physical system and its performance. It should also be convenient for tradeoff studies and comparisons with other concepts. The following parametric description is general; specific applications would require a more detailed description.

Geometric parameters describe the augmentor in terms of the duct and shroud volume, the complexity of the nozzle, and the relationship between the nozzle and shroud. Figure 3 shows typical augmentor geometry; Fig. 4 defines the important parameters. The four area ratios and the mixing length are sufficient to describe the duct and shroud volume. The nozzle aspect ratio and pitch are sufficient to describe the nozzle for simple slot or lobe nozzle types. Multiple boundary-layer-control (BLC) nozzles or special nozzle shapes such as hypermixing nozzles would require additional parameters. The relationship between the nozzle and shroud can be characterized by the turning angle and the ventilation. The ventilation parameters are measurements of the physical characteristics of the entrained or secondary flow passages. They depend entirely on the specific augmentor configuration.

The principal augmentor performance parameters are defined in Fig. 5. The duct pressure loss and the nozzle velocity coefficient are measurements of the duct and nozzle flow efficiency, respectively. They are both independent of the design of the other augmentor components. The turning efficiency is a measure of the ability of the nozzle-shroud combination to turn the internal augmentor momentum. It depends entirely on the internal flow characteristics. The circulation lift coefficient is a measure of the ability of the wing-nozzle-shroud combination to turn the external momentum and depends on both the internal and external flow. However, good turning efficiency does not necessarily give good circulation lift.

The gross and isentropic augmentation are similar measurements of the ability of the nozzle-shroud combination to increase the nozzle thrust. The difference between the two definitions is the reference nozzle thrust used. Gross augmentation uses the actual nozzle-alone thrust while isentropic augmentation uses the product of actual mass flow and the nozzle ideal velocity, expanded isentropically to ambient static pressure. Neither is absolutely correct since the static pressure at the nozzle exit is less than ambient with the shroud on, causing the nozzle mass flow to be greater than for the nozzle alone. The definitions are used because it is usually possible to measure one or both of the reference thrusts. The shroud-on total thrust used should preferably be force measurements; exit rake momentum integration should be used only if a detailed total and static pressure survey is made of the exit. When the augmentation performance of different augmentor configurations is compared, the gross augmentation should be used since it excludes the nozzle losses. The nozzle velocity coefficient and the location of the nozzle pressure and temperature instrumentation should be documented for every investigation.

The entrainment ratio and net augmentation are measures of the augmentor pumping action and the subsequent momentum drag at forward speed. They can be calculated by integrating a velocity survey of the exit. Obviously, the more detailed the survey, the more accurate the integrated value will be. The accuracy of the measurement can be estimated by looking at the square root of the ratio of the integrated momentum to the measured force.

The choice of which performance parameters to optimize is critical. The tendency in past augmentor development has been to optimize gross or isentropic augmentation. In some applications, the highest gross augmentation does not give the best performance. For example, in applications requiring high circulation lift, more is gained by changing the geometry for better external flow turning (and lower augmentation) than by increasing gross augmentation.

Figure 6 defines the major aircraft operating parameters that affect augmentor design and performance. The general aircraft configuration selected to satisfy the mission requirements should define their range of values. Note that they are independent of the augmentor component design except for the duct Mach number, which depends on the duct area.

Empirical and Theoretical Data

The relationships between the various augmentor and aircraft parameters should be based on empirical data with a judicious use of theoretical/empirical analyses. The performance of augmentors is totally dependent on highly three-dimensional, turbulent mixing. Because of this inherent complexity, theoretical analysis of augmentors generally lags the experimental hardware.

All analyses must incorporate some degree of empiricism to account for the turbulent mixing process. In addition, some performance information such as exit static pressure must be specified to close the analysis. The simplest type of analysis is the two-dimensional, mass-momentum analysis of von Kármen.[1] With the addition of pressure loss and velocity profile distortion parameters, the analysis can be used to evaluate simple trends. It cannot be used to predict absolute results since it does not account for the actual augmentor or flow geometry.

The two-dimensional integral analysis of Ref. 2 uses empirical turbulence data from free-jet mixing to model the flow as well as the actual shroud geometry. However, the analysis is difficult to apply to complicated nozzle and inlet geometries and therefore is also limited to predicting trends rather than absolute results. Finite-difference numerical techniques can be used to model complex flow geometry and are flexible enough to use turbulence models ranging from mixing length theory to state-of-the-art turbulence models. References 3 and 4 are examples of two-dimensional analyses using finite-difference techniques. Although finite-difference analyses should predict absolute results, practical limitations such as required computer time and ability to model complex geometry usually limit their use to predicting trends from established empirical data bases.

Therefore, although theoretical analyses are not easily used to predict absolute values, they can be used to predict parametric trends and to point out critical areas for experimental study. For example, the change of gross augmentation with changing nozzle temperature ratio or inlet losses can be predicted.

The empirical data should, as much as possible, be from realistic large-scale models. Small-scale laboratory models should be used only for preliminary development. Augmentor technology has been slowed significantly because of problems in extrapolating geometry and performance from idealized small-scale models to complex large-scale hardware.

These problems do not appear to be scale effects, rather they are cumulative, secondary effects such as those due to sweep, taper, bracketry, and surface disturbances.

Aircraft-Augmentor Integration

A basic problem in augmentor integration is providing the volume in the aircraft for the ducting, nozzle, and shroud necessary for the desired augmentor performance. One example is the influence of the aircraft parameters on the duct geometry and performance. The duct design is a tradeoff between the wing aspect and thickness ratio, the engine pressure ratio and thrust loading, and the duct area, pressure loss, and Mach number. Figure 7[5] shows that percent thrust loss increases as duct pressure loss increases and it decreases as the engine pressure ratio increases. Thrust loss is especially significant below a pressure ratio of 2.0, even for low values of duct pressure loss. Thrust loss could therefore be minimized by use of a pressure ratio above 2.0, and with a duct pressure loss as low as possible. However, duct volume limitations and performance requirements for thrust loading severely compromise this decision by forcing the duct Mach number higher, thereby increasing the duct pressure loss. Figure 8 shows the thrust loading required and available for various aspect ratios and pressure ratios for the STOL design of Ref. 6, where 80% of the total thrust loading is ducted to the augmentor. Increasing the duct pressure loss by increasing the uninstalled thrust would increase the thrust loading available. Increasing the wing thickness would increase the thrust loading available at the expense of cruise drag. Increasing the wing loading would increase the thrust loading required.

Figures 7 and 8 point out the need for high-pressure-ratio engines on high-aspect-ratio, augmentor-wing aircraft. However, high-pressure-ratio engines are less fuel efficient than engines with low pressure ratio. One solution to this problem is to reduce the percentage of thrust to the augmentor by use of three spool engines. Another solution is to move the augmentor to the fuselage where more volume is available for lower pressures. Both solutions involve other tradeoffs such as reduced circulation lift or acoustic performance.

Another integration example is the selection of the nozzle and shroud for maximum augmentation performance. A nozzle-shroud combination is possible that will give a gross augmentation over 2. The problem is to provide the volume necessary for the shroud and nozzle and to design a minimum-weight, high-efficiency nozzle.

The purpose of the nozzle is to distribute the primary flow efficiently over the shroud throat so that the flow is completely mixed at the shroud exit. In many designs, the nozzles are also used to prevent separation on the diffuser walls. In some designs, the interaction between the nozzle flow and a coanda surface provides an efficient, internal turning device. The nozzle complexity is generally described by the relative number and types of individual nozzles, the size and simplicity of each individual type, and the mechanical relationships between the various parts. The nozzle volume, efficiency, and weight and their construction and maintenance costs depend on the nozzle complexity required. Tradeoffs can be made between the number and type of individual nozzles. For example, complete mixing can be achieved with fewer hypermixing lobe nozzles than with simple lobe nozzles.

The purpose of the shroud is to provide an efficient, converging inlet, a minimum area or throat where the nozzle flow is usually injected, and an efficient diffuser. Although curved diffusers have sometimes been shown theoretically to improve performance, straight diffusers usually perform better experimentally. An exception is the design discussed in Ref. 7, where the highly curved diffuser walls act more like a transition from the throat to the jet diffuser. The shroud volume is expressed in terms of the throat and exit area ratios and the mixing length. Figures 9 and 10 show the effect of exit area ratio and mixing length, respectively, on gross augmentation for several current configurations. Figure 11 shows the effect of exit area ratio on entrainment.

Although the three figures show that the performance of augmentors is highly sensitive to the specific configuration, some general comments can be made. The augmentation performance increases directly with mixing length for a given nozzle and with nozzle complexity at a fixed mixing length. The influence of area ratio on augmentation performance is not as strong and the augmentation peaks at an area ratio that depends on the specific configuration. The entrainment is a strong function of area ratio and nozzle complexity, but not of mixing length.

Garland (of De Havilland Aircraft of Canada) has suggested that, for a given configuration, maximum augmentation occurs when the secondary flow is near sonic at the throat. This suggests that an optimum shroud design should have the maximum mixing length possible and area ratios as small as possible, limited only by performance requirements and choked flow in the throat. Since large area ratios require more complex nozzles such as hypermixing and BLC nozzles, minimizing the area ratio would also minimize the nozzle complexity. An optimum design should also use high-pressure-ratio flow since, for a fixed nozzle thrust and shroud volume, both mixing length and area ratio increase with pressure ratio.

STOL Transport Design Considerations

The general criterion for a STOL transport is high thrust and moderate lift for takeoff and high lift for approach. An aerodynamically efficient solution is an internally blown, circulation control wing. The substitution of a thrust augmentor for the simple blown flap must, for the same powered-lift performance, offer significant advantages such as lower required thrust, lower gross weight, lower noise, or improved stability and control. Also, since the augmentor wing and internally blown flap aircraft have similar operating parameters, the internally blown flap can be used as a convenient reference for augmentor performance.

Figures 12 and 13 indicate that, for both two and three dimensions, the net takeoff thrust of agumentor wings becomes less than that of the internally blown flap at some forward velocity, even though the gross thrust of the augmentor wing is significantly higher at all forward speeds. This thrust lapse results from the momentum drag of the entrained flow and is analogous to the thrust lapse of high-bypass, low-pressure-ratio turbofan engines.

This problem cannot be avoided. The only solution is to minimize the thrust lapse by maximizing the net augmentation. This amounts to maximizing gross augmentation per entrained flow with flat exit velocity profiles and choosing a gross augmentation value that gives the desired net thrust at critical takeoff velocities. A gross augmentation of approximately 1.4 is likely the maximum that can be used effectively. High-pressure engines would increase the free-stream velocity where the augmentor net thrust equals that of the blown flap as well as reduce the duct and shroud volume required. An optimum augmentor would therefore be simple lobe nozzles and a shroud with low throat and exit area ratios.

The high lift required for approach can be obtained by directing the augmentor momentum at large angles to the free stream and preventing external flow separation on the top of the shroud, thereby creating large circulation lift. External flow separation can be controlled with appropriate blowing nozzles where separation occurs or by use of the inherent suction characteristic of agumentors as shown in Fig. 14.[10]

V/STOL Fighter Design Considerations

The general criterion for a V/STOL fighter is a high, trimmed vertical thrust with adequate margins at hover, and high lift and net thrust capabilities for transition and STOL performance. The key objectives of augmentor design are high gross augmentation and successful structural and balance control integration. Fighters tend to have the advantage of high pressure exhaust flow. However, the potential for large mixing length and area ratio values and reasonable required duct volume are limited by the high primary temperature and the low available volume. Figures 15 and 16 show several approaches to augmentor integration and their likely gross augmentation capabilities.

Wing or canard augmentors offer advantages in transition and STOL performance and potential elimination of auxiliary reaction controls. However, they are difficult to package because of the limited volume (especially thickness) available in the airfoils. Augmentors mounted in the fuselage or wing root areas have greater volume available, but they require auxiliary reaction controls for low speed and hover.

Concluding Remarks

The basic parameters of thrust augmentors were discussed, as well as their use in the aircraft integration process. Several general considerations were noted: using high-pressure-ratio engines to increase effective volume and maximizing net augmentation for STOL and gross augmentation for VTOL. While these general trends can be defined, actual design and performance of a specific augmentor configuration will be a function of a great many details. Therefore, a great deal of experimentation is required to develop a successful aircraft.

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Fig. 1 NASA augmentor wing jet STOL research aircraft.

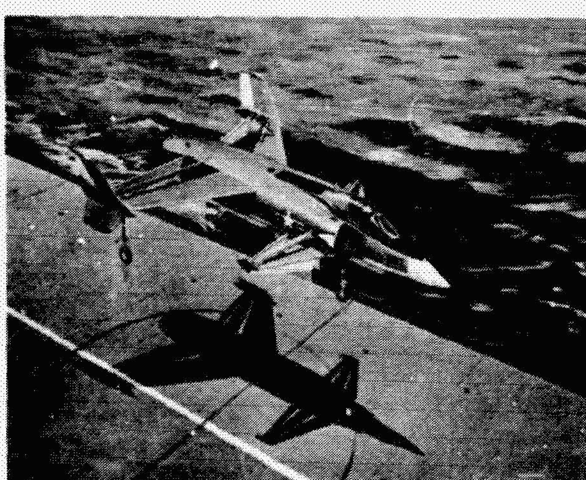

Fig. 2 Sketch of XFV-12A.

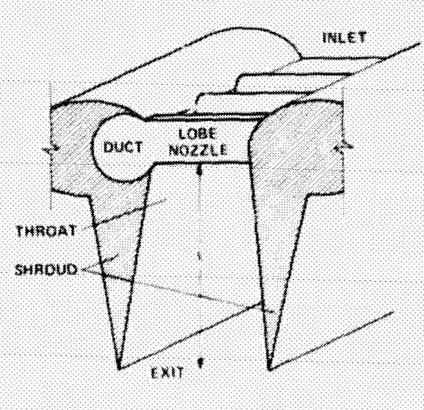

Fig. 3 Schematic of thrust augmentor.

PARAMETER	DEFINITION
• DUCT AREA RATIO	A_d/A_n
• THROAT AREA RATIO	A_t/A_n
• DIFFUSER AREA RATIO	A_e/A_t
• EXIT AREA RATIO	A_e/A_n
• MIXING LENGTH	ℓ/t
• NOZZLE TYPE	
• NOZZLE ASPECT RATIO, NAR	$(h/t)_n$
• NOZZLE PITCH, NP	$(p/t)_n$
• TURNING ANGLE, θ_t	
• VENTILATION	

Fig. 4 Thrust augmentor geometry parameters.

PARAMETER	DEFINITION
• DUCT PRESSURE LOSS, $\Delta P/P$	$(P_{IN} - P_{OUT})/P_{IN}$
• NOZZLE VELOCITY COEFFICIENT, C_V	$T_{shroud\ off}/(m_n V_{J_i})_{shroud\ off}$
• TURNING EFFICIENCY, η_T	$T/T_{\theta_T = 0}$
• CIRCULATION LIFT COEFFICIENT, C_{L_Γ}	$C_L - C_{L\ power\ off}$
• GROSS AUGMENTATION, ϕ_G	$T_{shroud\ on}/T_{shroud\ off}$
• ISENTROPIC AUGMENTATION, ϕ_I	$T_{shroud\ on}/(m_n V_{J_i})_{shroud\ on}$
• ENTRAINMENT RATIO	m_s/m_n
• NET AUGMENTATION, ϕ_N	$\phi_G - (m_s V_\infty)/T_{shroud\ off}$

Fig. 5 Thrust augmentor performance parameters.

PARAMETER	DEFINITION
• DUCT MACH NUMBER, M_D	
• NOZZLE PRESSURE RATIO, NPR	$(P_n)_{total}/P_\infty$
• NOZZLE TEMPERATURE RATIO, NTR	$(T_n)_{total}/T_\infty$
• THRUST LOADING, T/S	$(T_n)_a/S$
• VELOCITY RATIO, V_∞/V_J	V_∞/V_{J_a} OR V_{J_i}
• THRUST COEFFICIENT, C_J	$(T_n)_a/q_\infty S$

Fig. 6 Thrust augmentor operating parameters.

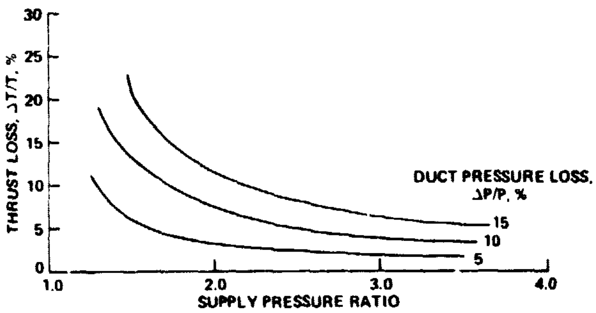

Fig. 7 Effect of duct supply pressure ratio and pressure loss on thrust loss.

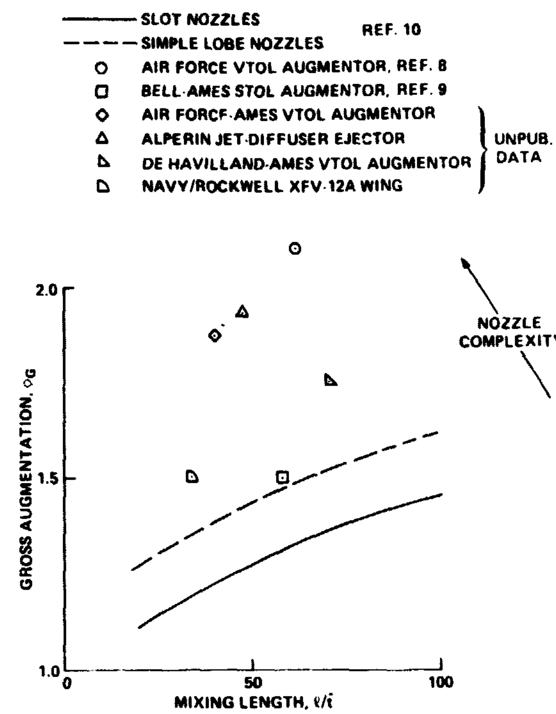

Fig. 10 Effect of mixing length on gross augmentation.

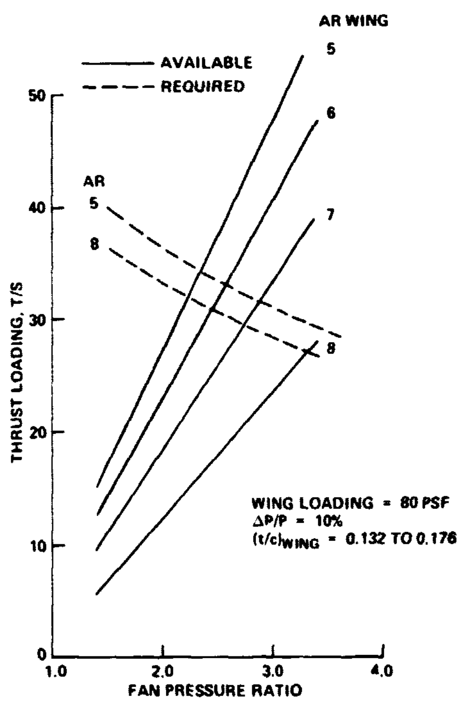

Fig. 8 Effect of fan pressure ratio and wing aspect ratio on installed thrust loading.

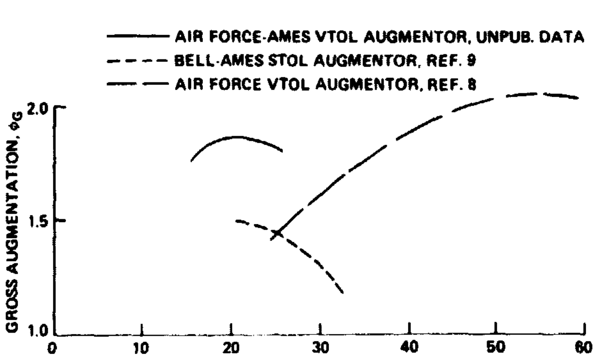

Fig. 9 Effect of exit area ratio on gross augmentation.

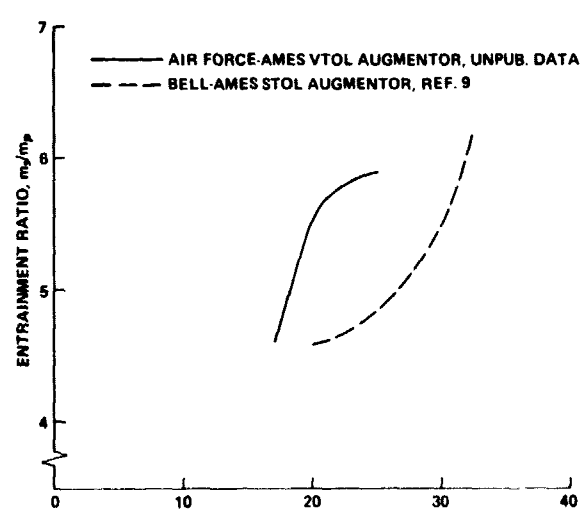

Fig. 11 Effect of exit area ratio on entrainment ratio.

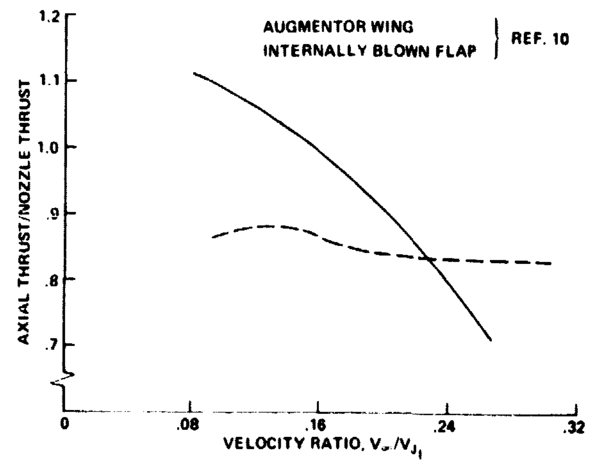

Fig. 12 Effect of velocity ratio on axial thrust: Two-dimensional models; $S_f = 30°$, $C_L = 3$, NPR = 2.3.

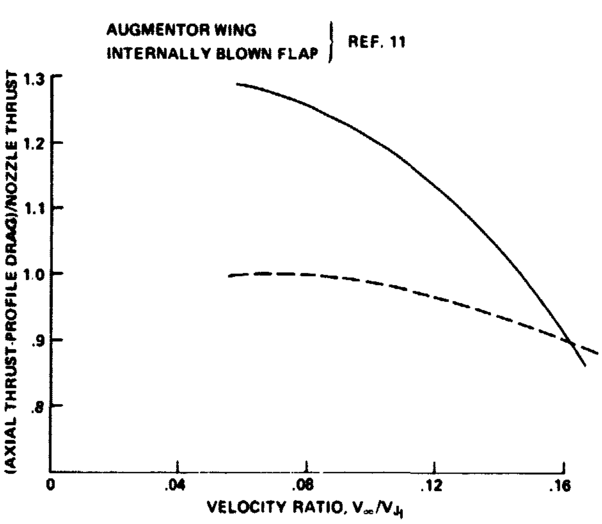

Fig. 13 Effect of velocity ratio on axial thrust: Three-dimensional model; $S_f = 15°$, wing aspect ratio = 8, $C_L = 4.5$, NPR = 1.80.

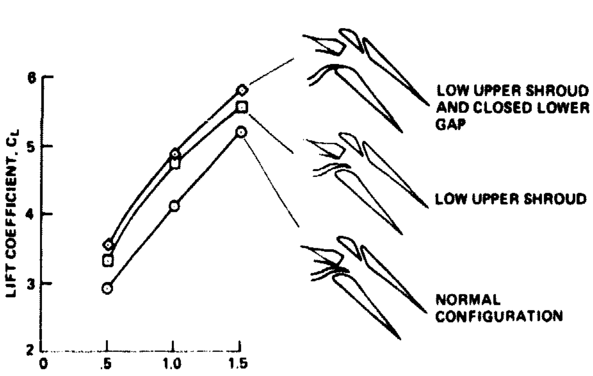

Fig. 14 Effect of geometry changes on lift characteristics of augmentor wing lobe nozzle, flap angle = 60°, angle of attack = 0°.

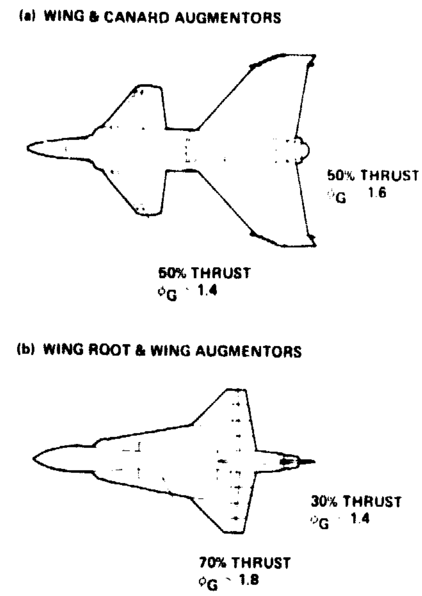

Fig. 15 V/STOL fighter-augmentor integration concepts.

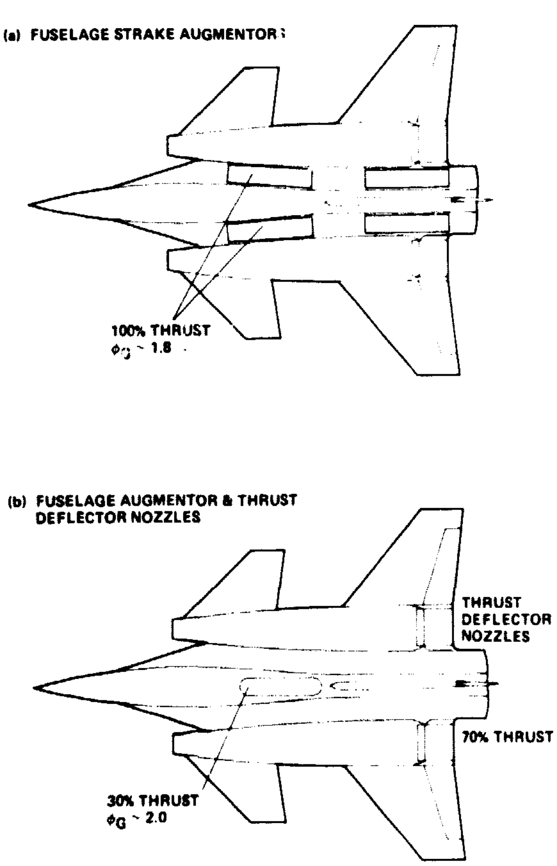

Fig. 16 V/STOL fighter-augmentor integration concepts.