The utilization limit lines for other wind speeds were obtained by the same procedure. Table 4 shows the total utilization, Fig. 5 being an example for the wind speed class of 15–20 knots of which the frequency is 19.94%. The utilization through the year comes out to be 86.7% for the SS-2 and 45.7% for the conventional flying boat.

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V/STOL Hover Control System Analysis

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The results of a study of the propulsion system/control system interface for several V/STOL hover control concepts in aircraft using the lift plus lift cruise propulsion concept are presented. The control concepts included are proportional reaction controls using lift engine compressor bleed air, engine thrust modulation, and engine thrust vectoring. The effects on control system performance of reaction control thrust augmentation by duct burning are shown. These control concepts are applied to three subsonic V/STOL strike-reconnaissance fighter aircraft of different gross weights, and a comparison of the concepts on the basis of bleed air requirements, thrust-to-weight ratio penalties, and lift engine operating limitations is made. It is shown that the use of duct burning augmentation and engine thrust vectoring control concepts produce significant performance improvements and simplifies lift engine design requirements.

Nomenclature

M = control moment required, lb-ft
I = moment of inertia, slug-ft^2
$\ddot{\theta}$ = required initial angular acceleration, rad/sec^2
ϕ = thrust vector angle for yaw control by engine thrust vectoring, deg
T = total vertical thrust, lb
W = aircraft vertical takeoff gross weight, lb

Introduction

THE majority of the methods currently proposed to provide hover and low-speed control for V/STOL aircraft involve use of the propulsion system either as the primary control thrust producer or as a source of bleed air for separate reaction controls. The use of the propulsion system as part of the control system creates a number of control system/propulsion system interface problems unique to V/STOL aircraft. This paper presents the results of a study of the propulsion system/control system interface for several V/STOL hover control concepts in aircraft using the lift plus lift-cruise propulsion concept. The two primary goals of the study were to determine the effect of control system requirements on lift engine design and to investigate methods of reducing the aircraft design and performance penalties associated with providing hover control.

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Aircraft

Preliminary designs for three V/STOL strike-reconnaissance fighter aircraft using the lift plus lift-cruise propulsion concept were prepared to provide realistic configuration, weight, and inertia information and to permit evaluation of engine and control system installation factors such as volume limitations and bleed air duct lengths. The three aircraft are shown in Figs. 1–3. The aircraft were designed for three different length missions, so that the resulting differences in their gross weights could be used to evaluate the sensitivity of control system parameters to gross weight and inertia. The aircraft design gross weights were 20,000 lb, 30,000 lb, and 40,000 lb.

Engines

The lift turbojet information used for the study was supplied by Continental Aviation and Engineering Corporation. Three lift engine designs of the same thrust class designed for 0, 6, and 10% of compressor airflow bleed capacity were used for each of the three aircraft, in order to vary the continuous bleed airflow supply for the reaction control system. Each of the three lift engines used the same compressor, and variations in bleed air capacity were obtained by resizing the turbine stage. The effects of altering the design point bleed of the lift engine are indicated in Fig. 4. This figure is intended to show typical characteristics only and does not represent any particular engine used in the study.

As the terms are used in this paper, "continuous" bleed refers to operation at the design point bleed capacity of the engine, and "demand" bleed refers to engine operation at greater than design point bleed or above the turbine inlet temperature limit line. Thus, bleeding any air from the zero

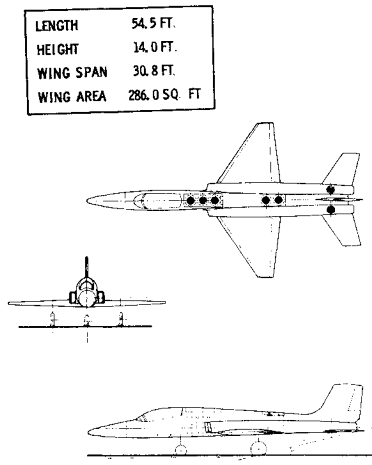

Fig. 1 Subsonic Fighter I, 40,000-lb design.

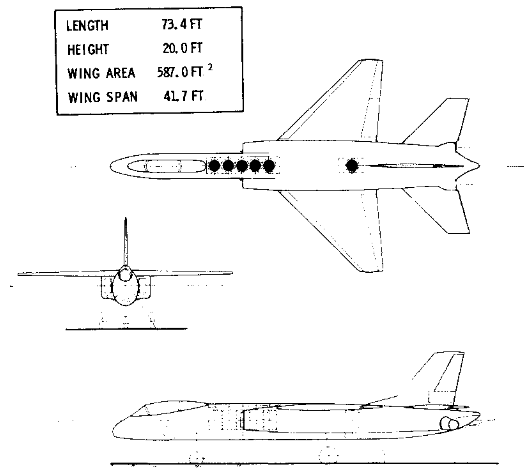

Fig. 3 Subsonic Fighter III, 20,000-lb design.

bleed design engine would be considered demand bleed. The lift-cruise engines used in the study were scaled from currently available information. No bleed air was taken from the lift-cruise engines for control purposes.

Control Systems

The following section describes the operating characteristics of the control systems considered in the study and defines the ground rules and assumptions used to simplify analysis. The reaction control systems used in the study are proportional controls with a constant total bleed airflow supply. The airflow is directed downwards and distributed to produce zero moments with the aircraft trimmed and no control inputs applied. The pitch and roll nozzles are variable area nozzles that produce a downward directed thrust in response to control inputs. The pitch nozzles have an additional sidewards thrust vectoring capacity to provide yaw control. The total bleed airflow supply is redistributed as required between the nozzles in response to control inputs. The roll control nozzles are located at the wingtips on each configuration, the forward pitch-yaw nozzle is located just ahead of the nose gear, and the aft pitch-yaw nozzle is located in the aft fuselage behind the thrust deflector nozzles of the lift-cruise engines.

Two different types of reaction control nozzles were used in the study: unaugmented nozzles using straight compressor bleed air, and bleed-burn nozzles that provide thrust augmentation by burning additional fuel at the nozzle inlet. The performance characteristics of the unaugmented nozzle are shown in Fig. 5, and the characteristics of the bleed-burn nozzle are shown in Fig. 6a. An operating temperature of 2400°R was used in the study to calculate the bleed-burn nozzle performance. The cross-sectional schematic diagram of a typical bleed-burn roll control nozzle is shown in Fig. 6b.

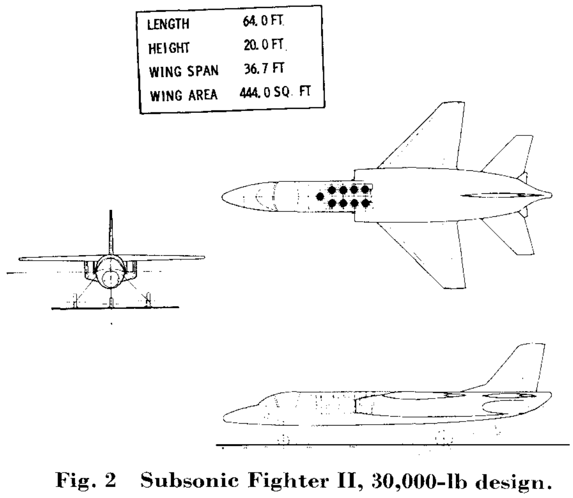

Fig. 2 Subsonic Fighter II, 30,000-lb design.

The size, weight, and performance information for the reaction control nozzles was supplied by Holley Aircraft Division of the Holley Carburetor Company. Pitch control by engine thrust modulation was obtained by fuel flow metering in response to control commands. Engine thrust vectoring a supply added yaw control was obtained by including a side to side thrust vectoring capacity in the engine nozzles in addition to the fore and aft vectoring capability required for transition from hover to conventional flight and for STOL operation.

The following general assumptions were used in conducting the control system analysis.

1) The control criteria used to size the moment producing capability of the control system were that the system produces the following initial angular accelerations: pitch axis = 0.6 rad/sec^2, roll axis = 1.2 rad/sec^2, and yaw axis = 0.4 rad/sec^2. It was further required that 100% of the preceding control powers be available about each axis separately and that 50% of the control powers be available about all three axes simultaneously.

2) Engine operation above the turbine inlet temperature limit was avoided. This ground rule results in an appreciable

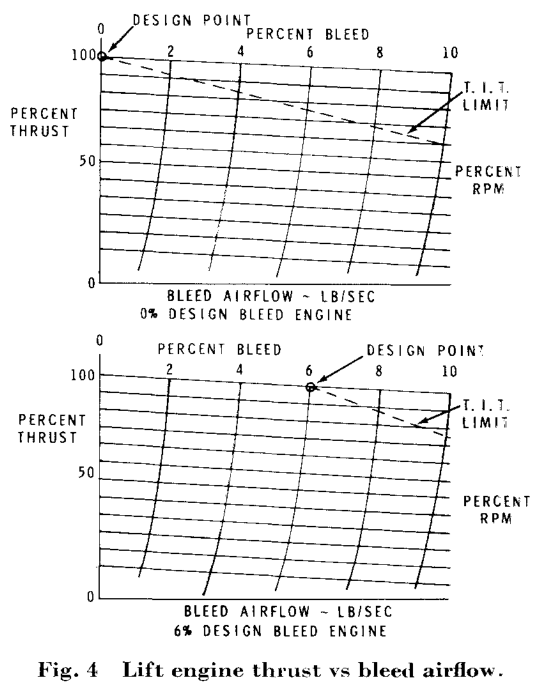

Fig. 4 Lift engine thrust vs bleed airflow.

thrust reduction during demand bleed operation as can be seen from Fig. 4. This ground rule was necessary at the time this study was conducted because of a lack of available information on the exact limits of engine overtemperature operation. During a future phase of the study, the use of intermittent engine overtemperature operation to supply peak demands will be investigated.

3) For thrust modulation, it was assumed that the engines were operating at 100% thrust with the aircraft trimmed, and control forces were generated by thrust reduction on the appropriate engines. This method of analyzing thrust modulation will not greatly effect the total installed thrust requirements, but it will cause greater thrust to weight ratio changes and, therefore, greater altitude coupling with attitude control inputs than if combined engine acceleration and deceleration is used to provide control. The total installed thrust requirements are about the same in either case, because if engine acceleration to produce control forces is used, the engine's normal operating condition must be less than 100% thrust to avoid overtemperature during control inputs.

4) To determine the temperature, pressure, and quantity of the bleed air available during thrust modulation, it was assumed that, in response to fuel flow metering, the engine operating conditions would follow a path closely approximating the lines of constant percent bleed shown on Fig. 4.

5) Since no specific handling qualities criteria pertaining to acceptable levels of axis cross coupling have been developed, it was required that the control systems produce only the moments required in response to control inputs and that no cross coupling due to control system operation be created. During analysis, this rule required compensation for the following effects:

a) pitch down moments created by roll control operation due to the location of the roll reaction nozzles aft of the c.g. as measured on the longitudinal axis; this moment was compensated for by either additional thrust at the forward pitch reaction control or by engine thrust modulation.

b) pitching moments and side forces created by vectoring either the pitch-yaw reaction control nozzle thrust or the engine thrust to produce yaw control because of the unequal magnitudes of either the fore and aft reaction control nozzle thrusts and moment arms or the unequal total engine thrusts of engines grouped fore and aft of the c.g.; these pitch moments and side forces were corrected by programing the reaction control or engine thrusts as required, and also by programing the vectoring angles.

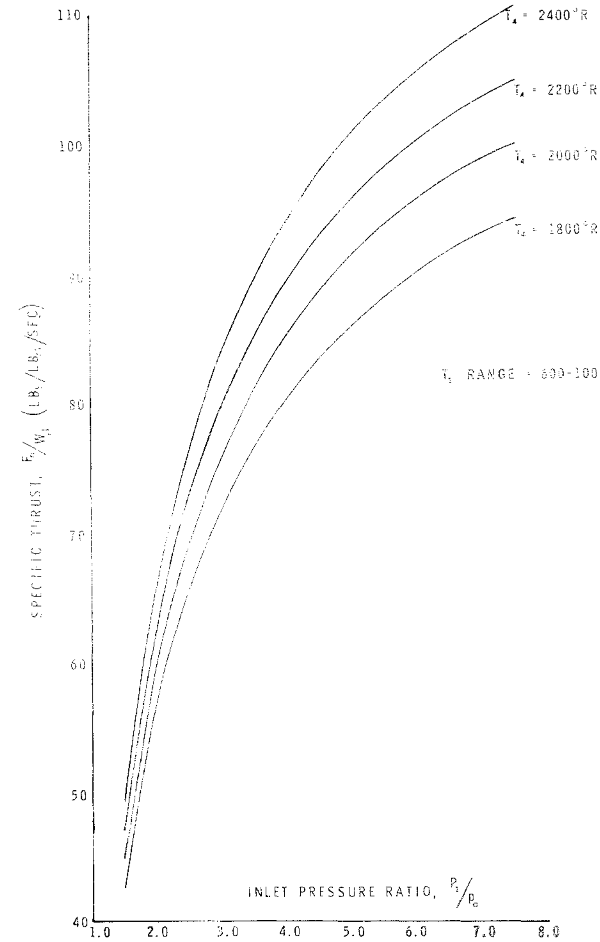

Fig. 6a Design performance, bleed and burn reaction control.

c) pitching moments caused by demand bleed operation of the lift engines because of asymmetric location of the lift engines about the c.g.; this effect was compensated for by modulating lift-cruise engine thrust during demand bleed operation of the lift engine.

6) It was assumed that the temperature, pressure, and bleed airflow available from all lift engines would be taken as the conditions available from the lift engines being used for thrust modulation when thrust modulation was used for pitch control. This assumption actually represents the minimum quality of bleed air available during thrust modulation.

7) The bleed-burn reaction control nozzles were assumed to require a minimum of 10% of their maximum airflow at all times to avoid flameout. When operating in this condition, the nozzles were assumed to produce negligible thrust. (This assumption was based on information supplied by the Holley Carburetor Company.)

8) Since it was not possible to create an accurate dynamic mathematical model of an engine for computer programing purposes, the bleed, thrust, rpm, pressure, and temperature characteristics of the lift engines were computed, assuming

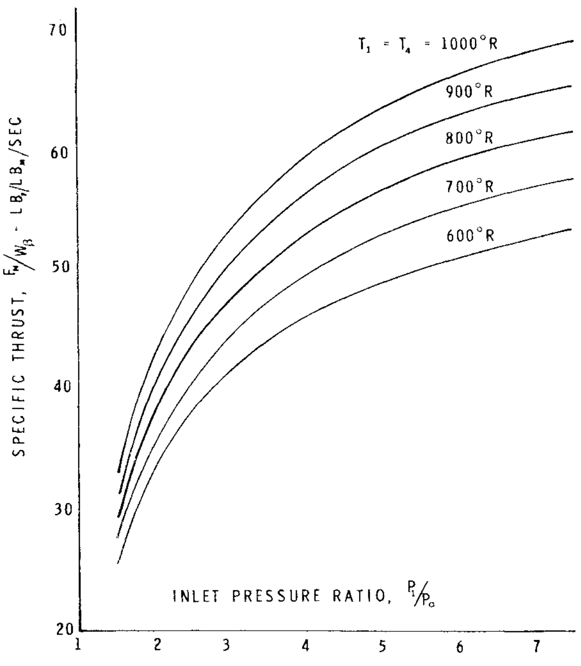

Fig. 5 Design performance, pure bleed reaction control.

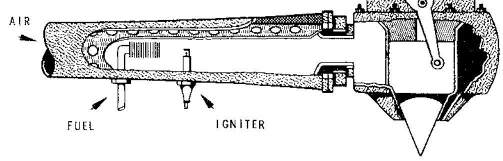

Fig. 6b Bleed and burn reaction control.

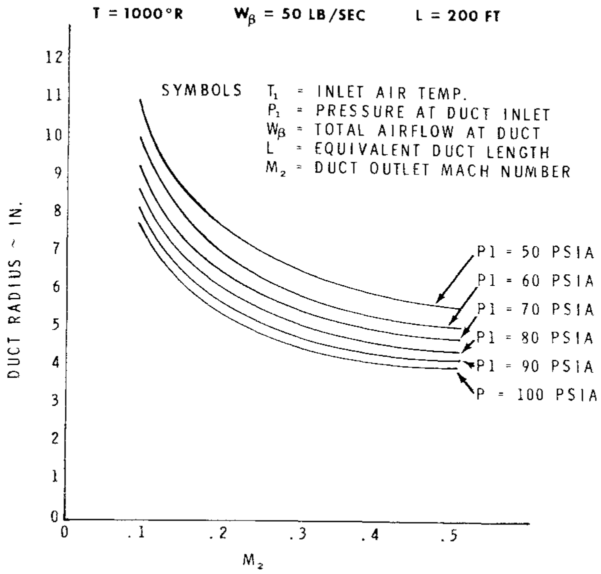

Fig. 7 Duct radius vs outlet Mach number.

steady-state operation at the conditions required to satisfy the control requirements for each of the control systems under consideration.

For each aircraft there were a total of eight possible hover control system combinations. These combinations, each of which was installed and analyzed as a separate system, are summarized in Table 1.

Using the previously listed assumptions, the following process was followed in determining the lift engine operating conditions with each control system for each of the previously specified control requirements.

1) The control system installation layout was prepared to determine control moment arms, reaction control locations, equivalent bleed air duct lengths, maximum allowable duct diameters, and other control system geometric characteristics.

2) The control moments required for each axis were computed assuming $M = I\ddot{\theta}$.

3) In control systems using thrust modulation for pitch control, the effects of the required thrust modulation were computed first. This was necessary for the combined control requirement case to provide the initial engine operating conditions in determining the bleed air requirements for the reaction control system.

4) The bleed air requirements of the reaction control system were than computed as follows:

a) The required nozzle thrust was computed.

b) Using the nozzle specific thrust curves for the type of nozzle being considered (see Figs. 5 and 6) and knowing the

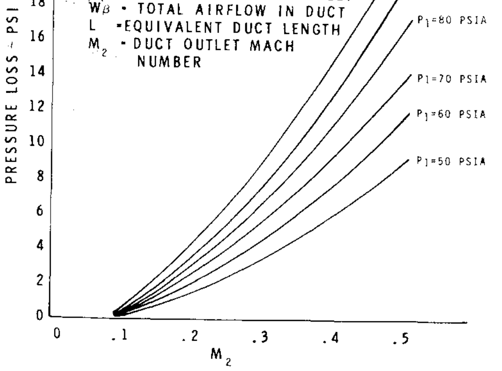

Fig. 8 Duct pressure loss vs outlet Mach number.

lift engine bleed air temperature and pressure as a function of engine rpm and percent bleed, the required total airflow for the reaction controls was computed. This process was iterative requiring successive approximations of airflow, air temperature, air pressure, duct diameter, duct pressure loss, and nozzle efficiency.

c) The duct losses for the reaction control systems were calculated assuming adiabatic flow in the ducts. To account for the geometric characteristics of the duct layout such as bends, joints, enlargements, and contractions, a method was devised by the personnel of Continental Aviation and Engineering Corporation to express these effects as equivalent additional lengths of duct. The resulting total equivalent duct lengths to each nozzle were used to compute the pressure losses in the ducts. The effects of changing inlet pressure and outlet Mach number on the duct diameter and pressure loss are shown in Figs. 7 and 8. The duct diameter required to hold a given outlet Mach number begins to increase rapidly below outlet Mach numbers of about 0.30 to 0.35, and the duct pressure loss rises sharply above this Mach number range. A roughly optimum duct outlet Mach number of 0.30 was used in the study.

5) In systems that used engine thrust vectoring for yaw control, the thrust vectoring requirements were computed last. This was done to make allowance for reductions in engine thrust because of modulation or bleed. The calculations for thrust vectoring were as follows. a) The required lateral forces were computed for each engine. b) The thrust vectoring angle ϕ required for each group of engines was determined. c) The thrust losses because of flow losses caused by deflecting the exhaust were found; the nozzle flow losses used in determining the thrust losses because of vectoring were based on tests conducted by Continental Aviation and Engineering Corporation with spherical engine nozzles. And d) The vertical thrust loss because of the change in direction of the thrust vector $T\ (1 - \cos\phi)$ was calculated for each engine.

Bleed Requirements

The maximum bleed requirements for each control system as determined in the study are shown in Figs. 9–11 as a function of the lift engine design point bleed. The particular control requirement that determines the maximum bleed required is not the same for each control system. The combination of control criteria that determines the maximum bleed requirement for a given control system will vary with the aircraft configuration and moments of inertia, and with variations in the control criteria specification itself. The critical requirements with respect to the bleed requirements for each control system are summarized in Table 2.

The method of presenting the bleed requirements used in Figs. 9–11 was chosen to show the effect of altering the engine design point on the total bleed requirements of the reaction

Table 1 Hover control system summary[a]

	Axis		
	Pitch	Roll	Yaw
Control systems	*BL*	*BL*	*BL*
	M	*BL*	*BL*
	BL	*BL*	*V*
	M	*BL*	*V*
	BB	*BB*	*BB*
	M	*BB*	*BB*
	BB	*BB*	*V*
	M	*BB*	*V*

[a] *BL* = unaugmented bleed reaction control; *BB* = bleed and burn reaction control; *M* = engine thrust modulation; *V* = engine thrust vectoring. These abbreviations are used on the figures to denote the systems to which the curves apply. The axes are specified in the following order on the curves: pitch, roll, and yaw.

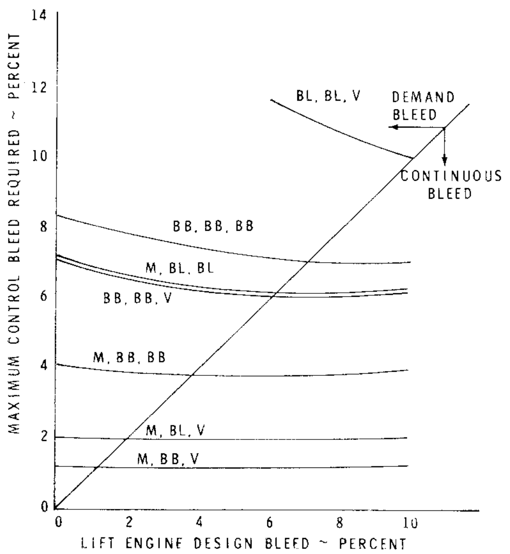

Fig. 9 Maximum control bleed required vs lift engine design bleed, 40,000-lb subsonic fighter.

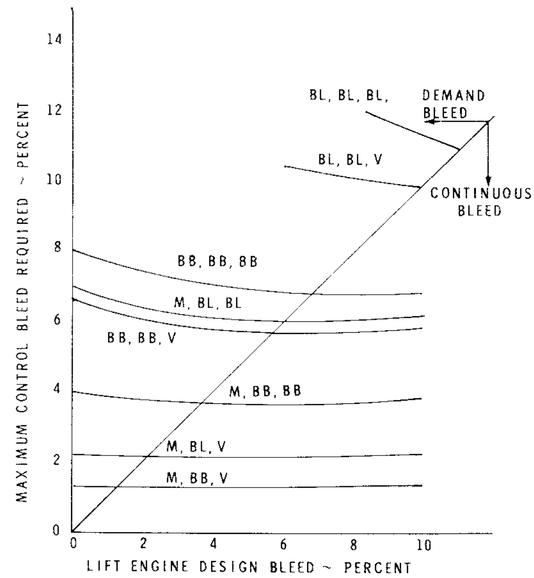

Fig. 10 Maximum control bleed required vs lift engine design bleed, 30,000-lb subsonic fighter.

controls. The 45° line on these figures represents the point for each control system at which the lift engine design point bleed is sized exactly for the maximum bleed required for control. For each control system, the part of the bleed air required curve lying to the left of the 45° line indicates the part of the total control bleed air requirements that is supplied by demand bleed operation of the lift engines. For the part of each curve lying to the right of the 45° line, the total bleed air requirement is supplied by the continuous bleed capacity of the engines.

The increase in bleed air required for each control system in the demand bleed region is primarily because of the manner in which demand bleed operation of the engines was treated in the study. Reference to the zero design bleed engine characteristics in Fig. 4 shows that taking bleed air from the engine while remaining within the turbine inlet temperature limit causes an appreciable reduction in engine rpm. Since the engine's total airflow is a function of rpm, a reduction in rpm gives a reduction in total airflow. Thus, if a given quantity of air is required to supply the reaction control system, this fixed quantity of air becomes a larger percent of the total engine airflow as engine rpm is decreased. A secondary effect that increases the bleed requirement in demand bleed operation is the reduction of the temperature and pressure of the bleed air as engine rpm is decreased. This effect leads to a lower reaction control nozzle specific thrust; and therefore, a higher airflow is required to produce the required control thrust.

The same general effect of demand bleed operation is true even if, instead of assuming that the engine always is operated within the continuous turbine inlet temperature (TIT) rating, a higher TIT limit for short period operation is defined. In

Table 2 Critical control requirement for maximum bleed air requirement[a]

Control system	Pitch 100%	Roll 100%	Yaw 100%	50% about all 3 axes
BL, BL, BL	...	...	...	X
M, BL, BL	...	...	X	...
BL, BL, V	X	...	...	...
M, BL, V	...	X	...	...
BB, BB, BB	...	...	...	X
M, BB, BB	...	...	X	...
BB, BB, V	X	...	...	...
M, BB, V	...	X	...	...

[a] This table applies to all three aircraft.

this case, the 45° line could be considered as the maximum rated bleed capacity of the engine during the specified time allowable for overtemperature operation.

An increase in the total bleed air required as the continuous bleed capacity of the engine is increased above the maximum control bleed required is shown for several of the control systems in Figs. 9–11. This increase is because of the reduction in the temperature and pressure of the design point bleed air as the engine's design point bleed is increased. This reduction is caused by the manner in which the bleed capacity of the engines was increased. The resizing of the turbine stage to permit higher compressor bleed results in a slightly lower design point rpm, which in turn gives lower temperature and pressure bleed air from the same compressor.

As it would be expected, the use of unaugmented bleed reaction controls for all three axes (*BL, BL, BL*) produced the highest bleed requirements. The engine bleed data available went to a maximum of 12% bleed for all three engines. This limit only permitted investigation of the all-bleed system for the 20,000 and 30,000 lb aircraft. A rough estimate of the bleed requirement for this system in the 40,000-lb fighter, assuming optimum engine bleed sizing, indicated that approximately 14% bleed would be required.

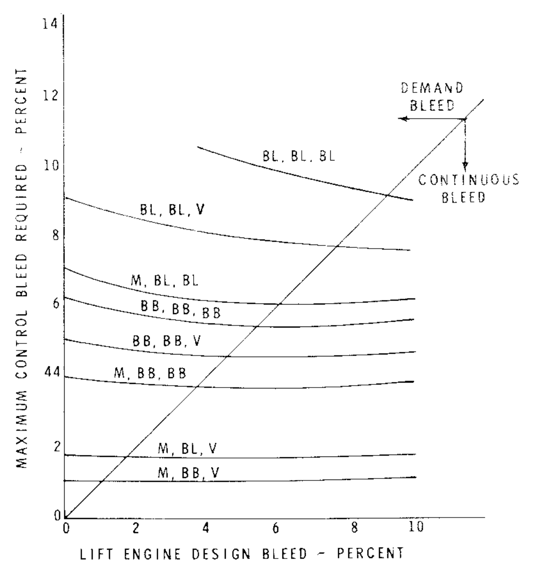

Fig. 11 Maximum control bleed required vs lift engine design bleed, 20,000-lb subsonic fighter.

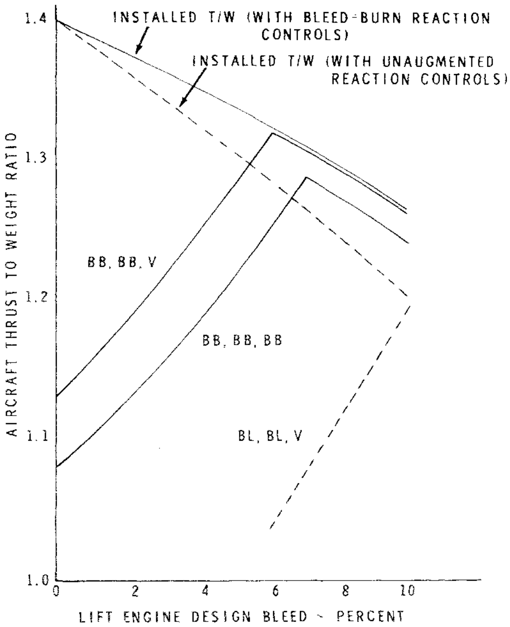

Fig. 12 Thrust-to-weight ratio vs lift engine design bleed, 40,000-lb subsonic fighter.

There are several engine and aircraft design factors that indicate that use of all bleed systems on aircraft in excess of 40,000 lb gross weight is impractical. The high-bleed requirements of the system create engine design problems in that a second turbine stage must be added when the engine bleed capacity exceeds 13–15%. This reduces the over-all engine thrust-to-weight ratio and introduces added complexity. In addition to engine problems, the size of the bleed air ducts required becomes excessive. The size of the pitch-yaw ducts begins to dictate the fuselage cross section, and it becomes difficult to fit the roll ducts into the wing

For the configurations used in the study, the pitch axis produced the largest bleed requirement for the reaction control system. The use of engine thrust modulation instead of reaction controls for the pitch axis produced approximately a 50% reduction in the total bleed requirement. This reduction included taking into account the reduction of engine speed and consequent reduction in bleed air temperature and pressure during thrust modulation.

The use of engine thrust vectoring instead of reaction controls for the yaw axis produced a 10–15% reduction in the bleed required over a system using reaction controls for all three axes. However, for systems using thrust modulation for pitch control, the yaw axis became critical in determining the total bleed requirements. In these systems, the use of vectoring produced a 50% reduction in the bleed requirement.

The use of bleed-burn controls in any control system instead of unaugmented reaction controls produced a 40–50% reduction in the total bleed requirements. This reduction included the allowance for the airflow required to avoid flameout in the burning nozzles. The use of bleed-burn controls, rather than unaugmented reaction controls, also reduced the sensitivity of the control system bleed requirement to changes in aircraft gross weight.

Thrust-to-Weight Ratio Effects

After the engine operating conditions for each control system had been determined, the thrust penalties and the resulting aircraft thrust-to-weight ratios for each combination of control criteria were found. The resulting aircraft thrust-to-weight ratios during control operation with the most critical control requirement are shown in Figs. 12–17 as a function of lift engine design point bleed.

Each of the three aircraft was initially sized for an installed thrust-to-weight ratio of 1.4 with the zero bleed design point lift engine. This installed thrust-to-weight ratio included estimated reingestion and suckdown losses, as well as engine inlet and nozzle losses, but it did not include any control losses. When the 6 and 10% bleed lift engines were installed to increase the continuous bleed air supply for the reaction controls, the aircraft gross weight was held constant, and the continuous bleed from the engines was distributed between the pitch and roll nozzles so as to produce no moment. Since the pitch and roll nozzles were deflected downwards, the continuous bleed air was recovered as vertical thrust.

The effect on the over-all aircraft thrust-to-weight ratio (T/W) of increasing the design point bleed of the lift engines, including the recovered thrust from the continuous bleed, is shown by the installed thrust-to-weight ratio curves for each

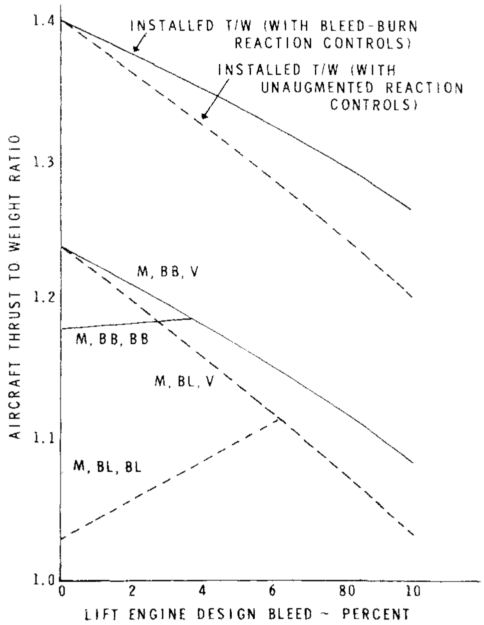

Fig. 13 Thrust-to-weight ratio vs lift engine design bleed, 40,000-lb subsonic fighter.

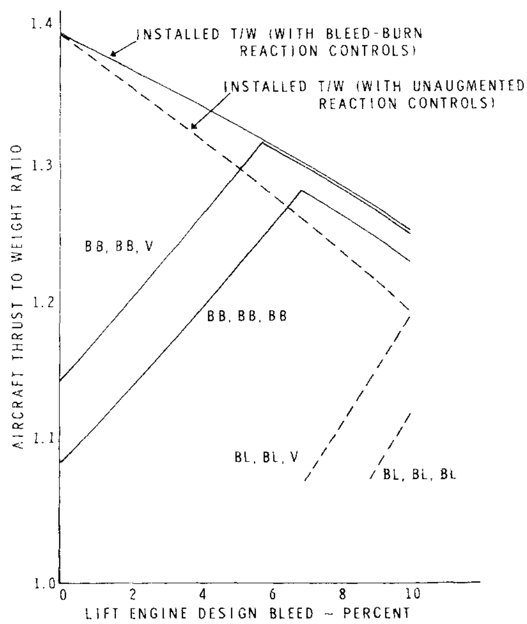

Fig. 14 Thrust-to-weight ratio vs lift engine design bleed, 30,000-lb subsonic fighter.

aircraft in Figs. 12–17. The reduction of installed T/W with increasing lift engine design point bleed results from the manner in which the lift engine design point bleed capacity was altered in the study. Since the same compressor was used for each engine and the turbine stage was rematched as the compressor bleed level was increased, a net thrust decrease resulted. The lower installed T/W curve indicated by the broken line shows the effect of varying the lift engine design point bleed and of using unaugmented reaction control nozzles to recover vertical thrust from the continuous bleed air. The upper solid installed T/W curve shows the same variation in engine design point bleed with bleed-burn reaction controls instead of unaugmented reaction controls. The difference between the two curves corresponds to the thrust augmentation provided by the bleed-burn nozzles. In all cases on these figures, the broken lines indicate the use of unaugmented reaction controls, and the solid lines indicate bleed and burn reaction controls.

The aircraft T/W curves for the control systems listed in Table 1 as shown in Figs. 12–17 include all thrust losses caused by the control system operation. In addition, the curves include the incremental aircraft weight changes due to differences in the weights of the control systems. The control system weights included estimates of the control system component weights such as air ducts, nozzles, and the additional weight added to engine nozzles to provide lateral thrust vectoring capability, but did not include changes in the aircraft structure that would be caused by variations in the control system. The control system T/W curves are presented for the control criterion that caused the largest T/W penalty for each particular system.

The sharp break in the control system T/W curves, as is shown, for example, in the T/W curve for the all bleed-burn control system in Fig. 12, corresponds to the point at which the lift engine design point bleed is exactly sized for the maximum required control bleed. This is the same design point bleed sizing that is represented by the 45° lines of Figs. 9–11.

The section of the control system T/W curves to the left of the break corresponds to demand bleed operation of the lift engines. Comparison of the aircraft installed T/W with the T/W during control operation for a given lift engine design point bleed in this demand bleed region shows the large T/W degradation associated with demand bleed engine operation. The decrease in aircraft T/W to the right of the break point is because of the increase in lift engine design point bleed capacity.

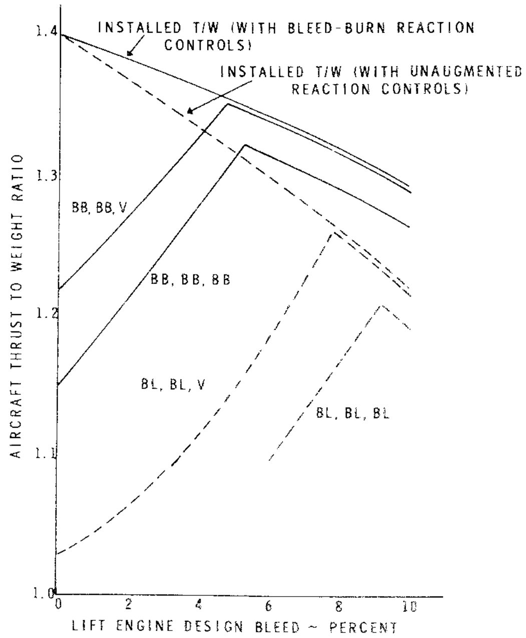

Fig. 16 Thrust-to-weight ratio vs lift engine design bleed, 20,000-lb subsonic fighter.

Because of the 12% maximum bleed limitation on the engine data available, it was not possible to completely determine the aircraft thrust-to-weight ratio variations with control system operation and lift engine sizing for the heavier gross weight aircraft. Since the most complete results were available for the 20,000-lb fighter, the following discussion will be with reference to the T/W curves for this aircraft (Figs. 16 and 17). The curves for all three aircraft are essentially similar in form, so the discussion generally can be considered as applying to all three aircraft.

The installed thrust to weight ratio curves and the individual control system thrust-to-weight ratio curves can be used to show two different aspects of the aircraft performance penalties associated with the provision of hover control. The intersection of the installed T/W curves with the zero lift engine design bleed axis for the study aircraft at a thrust-to-weight ratio of 1.4 represents the aircraft performance with no hover control capability. Moving the right along either

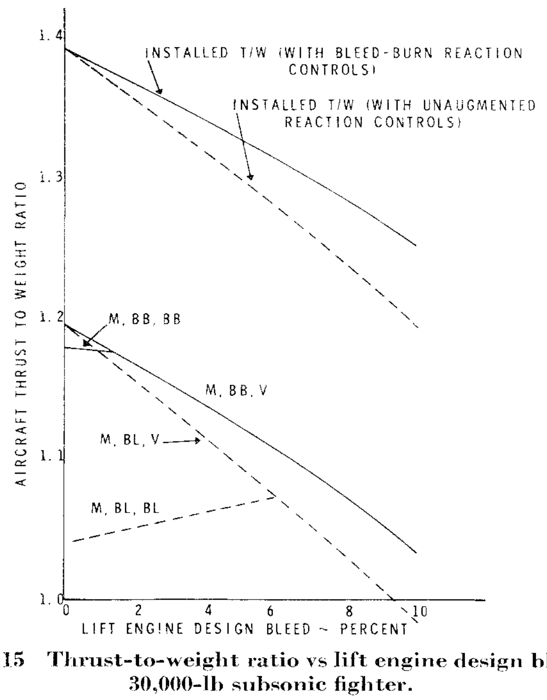

Fig. 15 Thrust-to-weight ratio vs lift engine design bleed, 30,000-lb subsonic fighter.

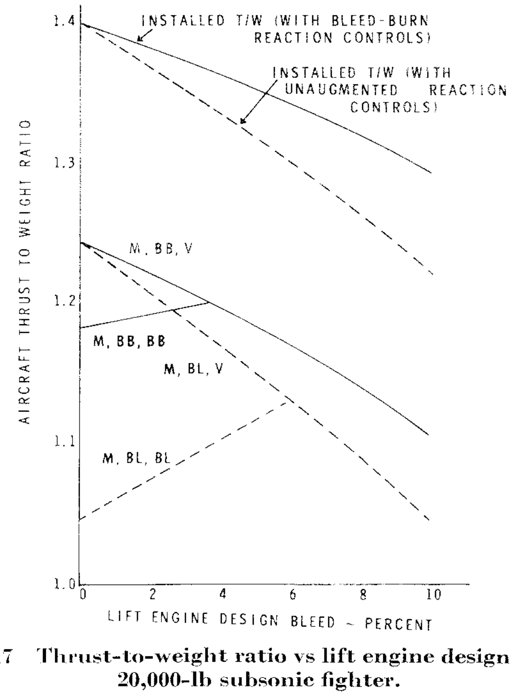

Fig. 17 Thrust-to-weight ratio vs lift engine design bleed, 20,000-lb subsonic fighter.

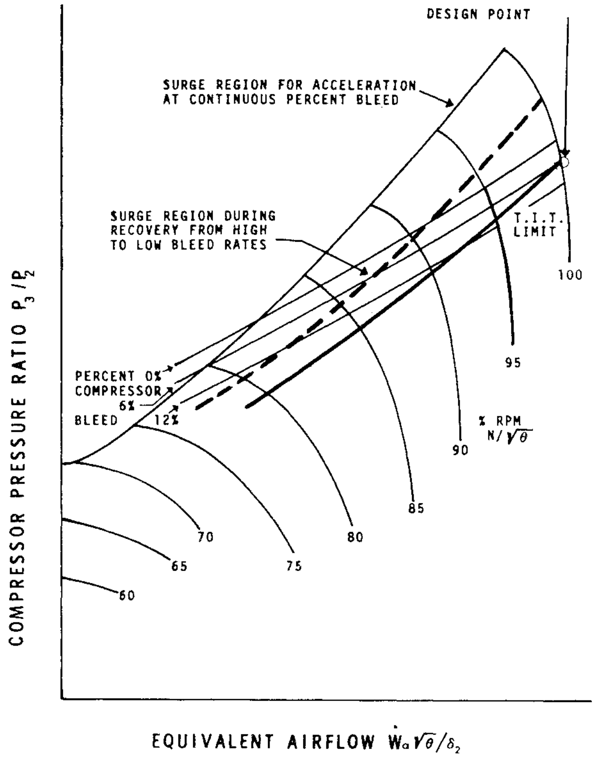

Fig. 18 Typical compressor characteristics.

the unaugmented or bleed-burn reaction control installed T/W curve represents the performance penalty for providing any given quantity of bleed air. If 100% of the bleed air were recovered as vertical thrust from the reaction control system, these two curves would represent the total performance penalties for providing a given level of control capability with either unaugmented or bleed-burn reaction controls.

The T/W curves for each control system represent the additional performance penalties due to the particular operating characteristics of the system. The break point for each curve represents the optimum matching of the lift engine and control system for maximum performance. At this optimum lift engine design point bleed sizing, the difference between the control system T/W ratio and the installed T/W ratio for the type of reaction controls used in the system is the additional performance penalty for the operating characteristics of the system

The T/W curve for the control system using unaugmented bleed reaction controls for all three axes (BL, BL, BL), shown in Fig. 16, indicates that the optimum lift engine design bleed for the control system is about 9.6%. At this design bleed, the difference between the control system T/W and the installed T/W for unaugmented bleed reaction controls is 0.027. The control requirement that determined the maximum bleed requirement for this system was that 50% of the maximum control power requirements be available about all three axes simultaneously. The thrust-to-weight ratio penalty, however, was greatest for supplying 100% of the yaw control power requirement. In this case, part of the reaction control thrust was deflected laterally to supply yaw control and was lost as vertical thrust.

The optimum engine bleed sizing for the control system using unaugmented reaction controls for pitch and roll and engine thrust vectoring for yaw (BL, BL, V) was determined by the 100% pitch control requirement. The maximum thrust-to-weight penalty, however, was produced by the 100% yaw control requirement. At the optimum lift engine design point bleed, the difference between the installed T/W for unaugmented reaction controls and the T/W for the control system was 0.005. This system produces a considerably smaller T/W penalty during operation than the system using reaction controls. This is because of the relatively small vertical thrust losses associated with engine thrust vectoring compared with reaction control deflection for yaw control. In addition, the use of engine thrust vectoring permits recovery of all reaction control thrust as lift through the pitch and roll nozzles.

The optimum lift engine bleed sizing for the control system using thrust modulation for pitch control and unaugmented reaction controls for roll and yaw (M, BL, BL), Fig. 17, is 6.0%. The maximum bleed requirement for this system is determined by the 100% yaw control requirement. At the optimum lift engine bleed, the difference between the control system T/W and the installed T/W for unaugmented reaction controls is 0.17. This T/W penalty is determined by the engine thrust reduction necessary to meet the 100% pitch control requirement.

If, in addition to thrust modulation for pitch control, thrust vectoring is used to provide yaw control (M, BL, V), the 100% roll control requirement determines the lift engine bleed design point. With bleed air required for only the roll controls, the thrust reduction due to demand bleed engine operation becomes negligible. For the configurations used in the study, it was desirable from a thrust to weight ratio standpoint to demand bleed zero design engines rather than size them for the small amount of bleed required. The thrust penalty for this control system was determined by the 100% pitch control requirement.

The use of bleed-burn reaction controls rather than unaugmented reaction controls in the aforementioned control systems appreciably reduced the thrust penalties for all of the control systems except those using thrust modulation. The thrust penalties for pitch control by thrust modulation are primarily a function of the engine thrust reduction required for control and are not greatly influenced by the reaction control system.

It can be seen from the previous control system discussions that there are generally two different control requirements that determine the hover control performance penalties. One criterion will determine the lift engine design point bleed required with the type of reaction control nozzles being used. This criterion, then, limits the maximum thrust-to-weight ratio available with no control inputs applied to the system. The second criterion determines the additional thrust-to-weight ratio changes that are caused by the most demanding control system operating conditions. The effect of this second criterion will determine the altitude coupling characteristics of the control system in response to a control input.

Considering both the installation and operating characteristics of the control systems included in the study, the system using bleed and burn reaction controls to provide pitch and roll control, and using engine thrust vectoring for yaw control produced the smallest installation penalties and the least altitude coupling effects in response to control inputs. The worst system, in both respects, was thrust modulation for pitch control and unaugmented reaction controls for roll and yaw control.

Additional Considerations

In addition to the control system bleed requirements and thrust-to-weight ratio penalties, several other factors related to engine operating characteristics must be considered in hover control system selection and design. These factors include response rates, limitations imposed by compressor characteristics, and turbine overtemperature limits.

An important control system parameter with respect to determining the maneuver control power requirements for V/STOL aircraft is the control system lag time or the time elapsed between the pilot's control input and the control response. It is desirable to have the lag time as short as possible, generally less than 0.1 sec.

The time lags for the reaction controls and thrust vectoring engine nozzles which were investigated in the study were on the order of 0.1 sec or less. The best response times estimated for thrust modulation of the lift engines were 0.2–0.3 sec; and because of their higher moments of inertia, the lift-cruise engine response times were somewhat higher. The response times for thrust modulation may dictate higher maneuver control power levels than would be required for reaction controls or thrust vectoring.

The assumption, which was made for the study, of continuous lift engine bleed under steady-state conditions at the bleed level required by the maximum control demand does not account for some of the more important dynamic characteristics of the lift engine. Since the design point bleed sizing of a lift engine has an appreciable effect on its thrust-to-weight ratio, the use of intermittent bleed by operating the engine in an overtemperature or overspeed condition for short periods to supply bleed air for peak control demands may be desirable to permit reduction of the design point bleed of the engine. Preliminary investigations of the problems associated with this type of engine operation show that certain limitations are imposed by the engine's dynamic characteristics.

Figure 18 shows the typical compressor characteristics for an engine designed for 6% continuous bleed. With the engine operating at rated speed and design bleed, an increase in the bleed level at constant speed will move the compressor away from surge conditions and into the turbine overtemperature region. When the engine is returned to design point operating conditions from a higher intermittent bleed at constant speed, the surge region for acceleration at continuous bleed no longer applies. When the intermittent bleed air is returned to the engine, the pressure behind the compressor final stage is higher than under normal conditions. The greater the rate at which the intermittent bleed air is returned to the engine, the higher the pressure rise at the compressor final stage becomes. Under these conditions, the engine surge margin is sharply reduced, as is shown in Fig. 18. The effect of this reduction in surge margin on the use of intermittent bleed is to limit the rate at which the air can be returned to the engine.

Since engine overtemperature operation is also time-limited, the combination of the rate at which intermittent bleed air can be returned to the engine without creating surge conditions and the amount of time the engine can be operated in an overtemperature condition determines the limits on the amount of air that can be obtained by intermittent bleed.

Conclusions

Considering the bleed requirements, thrust-to-weight ratio penalties and engine operating limitations for the control systems investigated in the study, the following conclusions can be made:

1) The bleed requirements and thrust penalties for the use of unaugmented reaction controls for all three axes become prohibitive for aircraft with gross weights in excess of 40,000 lb if the control requirements specified are similar to those used in the study.

2) The use of thrust modulation for pitch control reduces bleed requirements considerably but causes appreciably more altitude coupling or thrust-to-weight ratio penalties than augmented reaction controls.

3) Engine thrust vectoring for yaw control reduces bleed requirements to a limited extent. When it is used with downward deflected reaction controls for pitch and roll, it practically eliminates altitude coupling with control inputs.

4) Bleed and burn reaction controls introduce additional complexity into the control system, but this factor is offset by large reductions in bleed air requirements and thrust penalties.

5) The best reaction control system for the reduction of bleed requirements, thrust penalties, and altitude coupling was the combination of bleed-burn reaction controls for pitch and roll control with thrust vectoring for yaw.

6) The thrust-to-weight ratio gains that can be obtained by the use of intermittent bleed to reduce the design point bleed of the lift engines will be limited by the compressor surge characteristics and the time limit for engine overtemperature operation.