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PRELIMINARY STUDY OF VTO THRUST REQUIREMENTS FOR A V/STOL AIRCRAFT WITH LIFT PLUS LIFT/CRUISE PROPULSION

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ABS: A preliminary assessment was made of the VTO thrust requirements for a supersonic (Type B) aircraft with a Lift plus Lift/Cruise propulsion system. A baseline aircraft with a takeoff gross weight (TOGW) of 13 608 kg (30,000 lb) was assumed. Pitch, roll, and yaw control thrusts (i.e., the thrusts needed for aircraft attitude control in the flight hover mode) were estimated based on a specified set of maneuver acceleration requirements for V/STOL aircraft. Other effects (such as installation losses, suckdown, reingestion, etc.), which add to the thrust requirements for VTO were also estimated. For the baseline aircraft, the excess thrust required for attitude control of the aircraft during VTO and flight hover was estimated to range from 36.9 to 50.9 percent of the TOGW. It was

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SUMMARY

A preliminary study was made of the VTO thrust requirements for a supersonic (Type B) aircraft with a Lift plus Lift/Cruise propulsion system. In this proposed propulsion system, the lift and lift/cruise engines are not interconnected; and, as a result, the engines must be oversized to provide excess thrust needed for attitude control in the VTO and flight hover mode. For this study, a baseline aircraft having a TOGW of 13 608 kg (30 000) was assumed. Pitch, roll and yaw control thrusts (i.e., the thrusts needed for aircraft attitude control in the flight hover mode) were estimated based on a specified set of maneuver acceleration requirements for V/STOL aircraft.

In this study, different values of thrust split between Lift and Lift/Cruise engines were considered. The thrust split is shown to have a direct influence on the relative location of these engines about the aircraft center of gravity. For pitch and yaw control, the excess thrust required varies inversely with the total spacing between Lift and Lift/Cruise engines. Roll control which is provided by engine bleed flow exhausted through wing tip reaction jets is unaffected by the thrust split and the spacing between the respective engines.

For the baseline aircraft, the total excess thrust required for attitude control of the aircraft during VTO and flight hover was estimated to range from 36.9 to 50.9 percent of the TOGW.

Other effects (such as installation losses, suckdown, reingestion, etc.), which add to the propulsion system thrust requirements were also considered. The excess thrust requirement associated with these other effects was estimated to be 29.5 percent of the TOGW.

It was concluded from this preliminary study that the total thrust requirements for this aircraft/propulsion system are large and significant. In order to achieve the performance expected of the aircraft/propulsion system, reductions must be made in the excess thrust requirements.

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INTRODUCTION

For some time, the Navy has been interested in developing V/STOL aircraft which can be deployed from small ships in its sea control fleets. One part of this proposed V/STOL aircraft development program deals with an aircraft type known as the "Type B". The Type B is a supersonic interceptor/attack aircraft with V/STOL capability, having a specified maximum VTO gross weight of 15 876 kg (35 000 lb). Recent plans announced by the Navy for Type B aircraft (ref. 1) show a development starting date in the early 1980's and an IOC date of 1995.

A number of different propulsion system concepts have been proposed for the Type B aircraft (e.g., Lift + Lift/Cruise, Remote Auxiliary Lift System (or RALS) and the Augmentor Ejector). In this paper, only the Lift + Lift/Cruise propulsion system is considered, although much of the discussion herein is also applicable to the RALS.

In general, when we consider an aircraft with VTO capability, we are inclined to think in terms of VTO thrust requirements only slightly in excess of the TOGW. And since most new supersonic combat aircraft of today have thrust-to-weight ratios near one, it would seem that VTO capability could be provided without significant changes in current thrust-to-weight values. However, in a V/STOL propulsion system which is uncoupled (i.e., one in which driver engines are not connected by cross-shafting), power cannot be transferred to provide unbalanced lift for attitude control during VTO. And with the Lift plus Lift/Cruise propulsion system (which has uncoupled engines), all engines must be oversized to provide the excess thrust or lift needed for control in the VTO mode.

In this paper, VTO thrust requirements are examined for Type B aircraft powered by a Lift plus Lift/Cruise propulsion system. Tradeoffs are shown between control thrust requirements, thrust split and the location of Lift and Lift/Cruise engines about the aircraft center of gravity.

A fixed aircraft takeoff gross weight of 13 608 kg (30 000 lb) was assumed for this study. This assumed weight is consistent with estimates arrived at from conceptual design studies (refs. 2 and 3) of Type B, V/STOL aircraft with L + L/C propulsion.

DESCRIPTION OF TYPE B AIRCRAFT

WITH LIFT PLUS LIFT/CRUISE PROPULSION

Figure 1 is a sketch of one of the proposed V/STOL, Type B aircraft configurations with L + L/C propulsion. This particular aircraft (fig. 1) has two lift engines and two lift/cruise engines with thrust vectoring nozzles.

During VTO and flight hover, part of the total lift is supplied by vectoring the thrust of the L/C engines downward. The rest of the required lift is supplied by the vertically mounted lift engines. Balance of the aircraft in pitch, roll and yaw is provided by reaction jet forces. Pitch control is produced by changing the fractional lift generated by L and L/C engines (while holding total lift constant); roll control is provided by lift engine bleed air which is ducted to wing tip nozzles; and yaw control is provided by lateral deflection of the L and L/C engine exhaust.

CONTROL REQUIREMENTS FOR VTO AND FLIGHT HOVER

Control specifications for V/STOL aircraft (taken from ref. 4) and applicable to Type B aircraft are listed in table I.

As stated in reference 4, aircraft such as the Type B, whose missions require extensive hover and low-speed maneuvering, should meet the maximum levels shown. Throughout this study, we will base our estimates of control thrust on the assumption that the maximum maneuver accelerations in table I must be realized. In order to meet these specified maneuver accelerations, excess thrust (over and above that needed for lift) must be provided. This requires oversizing both the Lift and Lift/Cruise engines.

EXCESS THRUST REQUIREMENTS FOR VTO

Representative values of mass moments of inertia for a Type B aircraft with Lift plus Lift/Cruise propulsion and with a TOGW of 13 608 kg (30 000 lb) are listed in table II.

The control thrust requirements for VTO depend directly on the mass moments of inertia of the aircraft. And the moments of inertia can change significantly with the particular design of the aircraft. In arriving at the values in table II, various proposed design configurations for V/STOL Type B aircraft were reviewed. An assessment of the mass moments of inertia was also made using a Lewis digital code known as the "Aircraft Mission Analysis Code" (AMAC).

The values listed in table II are considered representative values and are comparable to those given in reference 5 and also to the values computed with AMAC.

Throughout this study, the moments of inertia given in table II were assumed constant for all thrust splits between L and L/C engines and for all corresponding locations of these engines relative to the aircraft center of gravity (c.g.). Thus, we are basically considering an aircraft in which the dimensions, scale factor, TOGW and weight distribution are fixed, regardless of the thrust split between engines.

The moments of inertia listed above were used to estimate pitch, yaw and roll control thrust requirements. In what follows, we will consider the individual effects of pitch, yaw and roll on the aircraft VTO thrust requirements. We will also consider other effects such as propulsion system/aircraft "induced effects" (suckdown, reingestion, etc.). We will then combine these effects to arrive at an estimate of the total installed thrust for a representative Type B aircraft with L + L/C propulsion.

PITCH CONTROL

Consider a typical Type B aircraft with a L + L/C propulsion system arrangement as depicted in figure 2. If we assume the aircraft to be in a stationary hover position, the forces acting on the aircraft are shown in the free-body diagram of figure 2. Referring to this diagram, we have:

For translational equilibrium,

$$\Sigma F_y = 0; \; T_L + T_{L/C} = TOGW \tag{1}$$

For rotational equilibrium,

$$\Sigma M_{c.g.} = 0; \; T_L \times a = T_{L/C} \times b \tag{2}$$

Combining equations (1) and (2), we get:

$$\frac{T_L}{TOGW} = \frac{b}{(a + b)} \tag{3}$$

and

$$\frac{T_{L/C}}{TOGW} = \frac{a}{(a + b)} \tag{4}$$

Equations (3) and (4) show that the respective spacings of L and L/C engines about the aircraft c.g. are dictated by the thrust split between these engines.

Now, consider the excess thrust requirements for pitch control. The excess thrust needed to meet the pitch control requirements of table I are as follows:

The relative change in lift engine thrust for pitch control is

$$\frac{\Delta T_{L,pitch}}{T_L} = \frac{I_y \ddot{\theta}}{b \times (TOGW)} \tag{5}$$

And the relative change in L/C engine thrust for pitch control is

$$\frac{\Delta T_{L/C,pitch}}{T_{L/C}} = - \frac{I_y \ddot{\theta}}{a \times (TOGW)} \tag{6}$$

($\ddot{\theta}$ is considered positive for counter-clockwise rotation.)

Dividing equation (5) by equation (6), we have:

$$\frac{\dfrac{(\Delta T_{L,pitch})}{(T_L)}}{\dfrac{(\Delta T_{L/C,pitch})}{(T_{L/C})}} = -\frac{a}{b} \tag{7}$$

Equation (7) states that for pitch control with balanced lift, the relative changes in excess thrusts of L and L/C engines are proportional to the lever arm ratio and opposite in direction.

Likewise, from equations (3), (4) and (7), we have:

$$\frac{\Delta T_{L,pitch}}{\Delta T_{L/C,pitch}} = -1 \tag{8}$$

Equation (8) states that for rotation in the pitch plane, with no translation, the excess thrusts of L and L/C engines must be equal and opposite.

Combining equations (3), (4), (5) and (6) gives the maximum total excess thrust required for pitch control; that is,

$$\frac{\left|\Delta T_{L,pitch}\right| + \left|\Delta T_{L/C,pitch}\right|}{TOGW} = \frac{2\, I_y\, \ddot{\theta}}{(a + b)\ (TOGW)} \tag{9}$$

In equation (9), the maximum value of total excess thrust for pitch control is represented by the sum of the absolute values of the individual terms.

Figure 3 shows the relationship between total excess thrust required for pitch control and the spacing between the L and L/C engines. This figure was constructed from equation (9) and is based on the following assumed values:

$$TOGW = 13\ 608\ \text{kg}\ (30\ 000\ \text{lb}),\ I_y = 135\ 580\ \text{kg m}^2\ (100\ 000\ \text{slug ft}^2)$$
$$\text{and}\ \ddot{\theta} = 0.8\ \text{rad/sec}^2$$

The curve in figure 3 is actually a curve of constant potential torque in the pitch plane. This curve represents the minimum constant torque needed to satisfy the pitch control requirements. Points to the left and below this curve represent torques which are less than required for pitch control, and points to the right and above this curve represent torques greater than required for pitch control.

Figure 3 shows that the excess thrust required for pitch control drops off significantly as separation between L and L/C engines increases. As indicated here, the larger the separation between engines, the smaller the excess thrust requirement for pitch control. Since engine size and weight are also lowered with reduced thrust requirements, it appears advantageous to have the separation between engines as large as possible. But there is a practical limit to the maximum spacing of engines about the aircraft c.g. Factors such as lift engine containment inside the fuselage, inboard fuel arrangements, storage of electronic equipment, storage of armament and maintaining an integrated low-drag aerodynamic configuration are important in the overall design of the aircraft. For the reference aircraft being considered here, a practical range of separation between engines was selected to be between 5 and 8 meters (16.4 to 26.3 ft). This selected range is indicated on the curve in figure 3. Within this range, figure 3 shows that the minimum value of excess thrust required to provide the necessary pitch control varies from about 32 percent for the minimum separation down to about 22 percent for the maximum separation.

Because of the need to maintain a constant lifting force on the aircraft at all times during hover, any imposed increase in thrust on one of the engines must be offset by an equal thrust decrease on the other engine. The absolute amount by which the thrust of either engine must be changed for pitch control depends on the nominal thrust split. For example, consider the extreme nominal thrust split for which $T_{L/C}/T_L = 80/20$. For this thrust split, the maximum allowable relative increase in L/C engine thrust is 25 percent. And for this level of L/C engine thrust increase, the L engine thrust would decrease to zero, so that the total lifting force is constant and equal to the TOGW.

Obviously, the L engine thrust cannot be allowed to fall to zero, or even to a thrust level approaching zero. From a practical standpoint, there is a limit to the relative amount by which engine thrust may be lowered and, at the same time, provide an acceptable engine thrust response rate for attitude pitch control.

With reference to figure 3, the curve shown there represents a minimum constant level of torque required to meet the pitch maneuver acceleration requirements. But for engine thrust splits which are large, the relative changes in lift engine thrust may be larger than desired for responsive control. This is illustrated in figure 4 which shows the relative thrust change required by the L engine as a function of total excess thrust for different nominal thrust splits. This figure indicates that for a fixed value of total excess thrust, the relative change in L engine thrust varies significantly with the thrust split. Within the expected range of engine separation, figure 4 shows that with a thrust split of 80/20, the relative change to L engine thrust may be as great as ± 80 percent. From a control standpoint, a change of this magnitude may have an unfavorable effect on the response rates of the propulsion system.

The significant point of the foregoing discussion is that with L + L/C propulsion, the pitch control of the aircraft is provided by changing the output thrust of both engines. And the relative change in the L engine thrust output may be extreme for thrust splits which are large. As a result of this, control considerations may play a dominant role in the selection of the thrust split between engines.

YAW CONTROL

Consider the forces acting on an aircraft hovering in equilibrium as depicted in figure 2. Recalling that for balance in the pitch plane, the total lift ($T_L + T_{L/C}$) must equal the TOGW as stated by equation (1). Also, the pitching moments about the aircraft c.g. must be equal and opposite as stated by equation (2). The lateral torque required to meet the yaw maneuver acceleration requirements ($\ddot{\psi}$ = 0.8 rad/sec^2) is given by:

$$\text{Lateral Torque} = I_z \ddot{\psi} = 141\ 000 \text{ Newton-meter } (104\ 000 \text{ lb-ft})$$

If we consider the individual engine exhaust streams to be deflected laterally through angles α and $-\alpha$ as measured from the vertical direction, then each exhaust stream produces a yaw torque in the same rotational direction. The magnitude of the lateral torque produced by the component forces is given by:

$$\text{Lateral Torque} = \pm(a\ T_L \tan\alpha + b\ T_{L/C} \tan\alpha) \qquad (11)$$

The sign convention used in equation (11) must be consistent with that of $\ddot{\psi}$ for indicating the rotational direction in the yaw plane.

The excess thrust needed to produce the required yaw acceleration ($\ddot{\psi}$ = 0.8 rad/sec^2) is shown in figure 5 as a function of spacing between L and L/C engines for various thrust deflection angles and thrust splits.

Each curve shown in figure 5 represents a constant lateral torque value of 141 000 Newton-meter (104 000 ft-lb). As stated earlier in this section, the practical range of separation between L and L/C engines was taken to be between 5 and 8 meters (16.4 to 26.3 ft). This range of separation is indicated in figure 5. Within this range and for the thrust splits shown, it appears that the minimum (or near minimum) excess thrust requirement occurs at a lateral deflection angle between 20 and 25 degrees. And from figure 5, the excess thrust needed to meet the yaw control requirement is on the order of 6.5 to 10.5 percent of TOGW.

In the foregoing discussion, we assumed that the lateral thrust deflection angles of the L and L/C engines are equal in magnitude but opposite in sign. As a consequence of this, a lateral force unbalance is created during yaw maneuvers for all nominal thrust splits ($T_{L/C}/T_L$) different than

50/50. Thus, under some flight conditions, subsequent corrections may be required to compensate for the force unbalance.

ROLL CONTROL

In the proposed Type B aircraft with L + L/C propulsion, wing tip reaction jets provide the thrust needed for roll control. In this configuration, compressor bleed air from the forward lift engine is ducted internally through the wings and exhausted through nozzles at the wing tip.

There are two possible arrangements which may be used for exhausting the bleed flow at the wing tip nozzles. In one arrangement, the bleed flow is directed downward from both wing tips; and roll control is achieved by modulating the amount of bleed flow sent to each wing tip nozzle. One advantage to this arrangement is that the downward directed bleed flow contributes to the lift. However, the bleed flow ducts in the wings must be large enough so that each is capable of carrying the total bleed flow.

In the other arrangement, the total bleed flow is divided and one-half of the flow is ducted to each wing tip. The flow ducts in each wing tip contain a tee-section with valves so that the bleed flow may be directed either upward or downward. By regulating the direction of the exhaust flow on each side, a coupling action is created which provides a turning moment for roll control. An advantage of this arrangement is that smaller flow ducts can be used. However, the flow system is more complex. Also, the bleed flow exhaust does not contribute to the lift.

More information is needed to determine which of these arrangements is better. For the purpose of this study, we will assume that roll control is provided by the former arrangement.

The torque required to meet the roll maneuver acceleration (specified in table II) is given by:

$$T_{roll} = I_x \ddot{\phi} = 37\ 960 \text{ Newton-meter } (28\ 000 \text{ lb-ft}) \qquad (12)$$

The moment arm applicable to this torque is taken as one-half of the aircraft wingspan. The wingspan, to some extent, is dictated by the ship deck spotting factor requirements. Based on proposed conceptual aircraft designs for the Type B (ref. 3, for example), a representative wingspan of 10.7 meters (35 ft) was selected. Using this value of wingspan and the roll torque given by equation (12), the bleed flow thrust required for roll control is estimated to be about 7117 Newtons (1600 lb).

In order to estimate the amount by which the lift engine(s) must be oversized to provide the bleed flow thrust needed for roll control, we assumed the following:

(a) Lift engine is a turbojet with an overall pressure ratio (OPR) of 8.0 and a thrust-to-airflow ratio of 785 Newtons/kg/sec (80 lb/lb/sec).

(b) (Lift engine thrust loss)/(Lift engine bleed flow) = 1413 Newtons/kg/sec (144 lb/lb/sec).

This estimate of lift engine thrust loss with overboard bleed was made from engine studies conducted with a digital program known as the Navy-NASA Engine Program, NNEP (ref. 6).

(c) (Thrust developed by wing tip jets)/(Lift engine bleed flow) = 550 Newtons/kg/sec (56 lb/lb/sec).

This value was estimated and is in agreement with the bleed thrust recovery given in reference 7.

The net effect of (a) and (b) above is that the overall net thrust loss with respect to lift engine bleed flow is approximately 863 Newtons/kg/sec (88 lb/lb/sec). And for the conditions assumed in (c) above, the bleed flow rate needed to provide the roll torque specified in equation (12) is about 12.9 kg/sec (28.5 lb/sec).

Because of the thrust penalty associated with bleed flow, the lift engine must be oversized to provide its share of the total lifting force for roll control. The relative excess thrust required by the lift engine for roll control is shown in table III for different values of thrust split.

The thrust split values shown in table III cover the range expected for the Type B aircraft with L + L/C propulsion. Thus, the excess thrust that must be supplied by the lift engine for roll control, i.e., $(\Delta T_{L,roll})$, is in the range of about 16.7 to 27.9 percent. And regardless of the thrust split, the value of excess thrust required for roll control is 11 165 N (2510 lb) or 8.4 percent of gross weight.

OTHER EFFECTS

Besides the excess thrust requirements for control, there are a number of other effects which must be considered for VTO and which add to the total excess thrust requirements. They include the following:

(a) Hot exhaust gas reingestion by engines

(b) Suckdown due to outflow of engine exhaust beneath the aircraft

(c) Engine operation during "hot day" conditions (90° F ambient air temperature)

(d) Installation losses resulting primarily from deflection of exhaust gas in thrust vectoring nozzles

(e) Vertical acceleration (or liftoff) of aircraft

Items (a) and (b) listed above are induced effects which are highly dependent upon the configuration of the aircraft, its height above the ground plane and the location of the installed engines. Normally, the assessment of these effects requires model testing of the aircraft/engine configuration. For the purpose of this discussion, we have assigned values for these induced effects which are considered to be reasonable estimates. Table IV lists the excess thrust requirements for each of the effects described along with comments pertinent to them.

The values listed in table IV for the factors were arrived at as follows: The effect of hot gas reingestion and hot day operation were determined from Lewis in-house studies conducted with the NNEP (ref. 6). The thrust loss associated with suckdown was taken from data given in reference 7. Installation losses include the inlet loss, the auxiliary power takeoff loss and the nozzle thrust deflection loss. The thrust loss from the inlet and the auxiliary power takeoff was taken to be 1.5 percent of the operating thrust. And the thrust loss from the 90° deflection of the nozzle exhaust was estimated, from reference 8, to be about 5.5 percent of the operating thrust. The value of excess thrust for vertical acceleration (5 percent of TOGW) is near the minimum level indicated in reference 4. For rapid deployment of aircraft, a higher VTO acceleration rate (possibly 0.1 g or greater) may be needed.

The thrust penalties associated with hot gas reingestion and suckdown exist only when the aircraft is operating in close proximity to the ground. These thrust penalties vanish once the ground effect is removed. Thus, the total excess thrust requirement listed in table IV represents a maximum (or near maximum) value which is applicable only when the aircraft is operating in close proximity to the ground plane.

PROPULSION SYSTEM WEIGHT

One of the penalties associated with excess engine thrust requirements is an increase in the total propulsion system weight. Figure 6 shows a relationship between propulsion system weight (i.e., total L + L/C engine weight - excluding nacelles and inlets) and propulsion system thrust for different thrust splits. (The propulsion system here was assumed to have two L/C engines and two L engines.) The curves in figure 6 were developed from a general correlation in the WATE-2 program (ref. 9) which relates relative engine weight to relative engine thrust as indicated below:

$$\frac{W_{eng}}{W_{eng,\ ref}} = \left(\frac{T_{eng}}{T_{eng,\ ref}}\right)^{\varepsilon} \tag{13}$$

The scaling exponent, ε, in equation (13) was determined to be 1.15 for the L/C engines and 1.20 for the L engines. The determination of ε

was made for the L/C engine by a curve-fit of data points computed with WATE-2; and for the L engine, ε was determined from engine weight data given in reference 10.

The conclusion to be reached from the data in figure 6 is that the requirements for excess thrust have a significant effect on the total weight of the propulsion system. The additional propulsion system weight ultimately translates into a larger and heavier aircraft to fulfill the specified aircraft missions.

SUMMARY OF RESULTS

A preliminary assessment was made of the VTO thrust requirements for a Type B aircraft with a L + L/C propulsion system. For this study, we assumed a baseline aircraft with a TOGW of 13 608 kg (30 000 lb).

Pitch, roll and yaw control thrusts were estimated based on a specified set of maneuver acceleration requirements for V/STOL aircraft. Other effects (such as suckdown, reingestion, etc.), which add to the thrust requirements for VTO were also considered. The excess thrusts associated with these individual effects are summarized in table V.

Table V shows that the total excess thrust requirement is relatively large. The requirement of excess thrust results in a corresponding increase in both the size and weight of the propulsion system. And the propulsion system weight increase ultimately translates into a larger and heavier aircraft to fulfill the specified missions for the Type B aircraft.

In order to achieve the performance expected of the Type B aircraft, efforts should be made to reduce the excess thrust requirements for VTO. The estimated excess thrust for control (36.9 to 50.9 percent of TOGW) is based on the assumption that the control moment requirement must be met about all axes simultaneously. It may be possible that this assumed requirement could be relaxed, thereby lowering the control thrust. In addition, the maneuver acceleration requirements should be studied. Reducing these maneuver values, perhaps to the minimum levels in table I, would result in a significant decrease in the control thrust.

APPENDIX - SYMBOLS

$\ddot{\theta}$	angular acceleration for pitch, rad/sec^2
$\ddot{\phi}$	angular acceleration for roll, rad/sec^2
$\ddot{\psi}$	angular acceleration for yaw, rad/sec^2
I_y	moment of inertia for pitch, kg m^2 (slug ft^2)
I_x	moment of inertia for roll, kg m^2 (slug ft^2)
I_z	moment of inertia for yaw, kg m^2 (slug ft^2)
$M_{c.g.}$	moment about center of gravity, N-m, lb-ft
T_L	lift engine thrust, Newtons (lb)
$T_{L/C}$	lift/cruise engine thrust, Newtons (lb)
a	distance from c.g. to lift engine, m (ft)
b	distance from c.g. to lift/cruise engine, m (ft)
$\Delta T_{L,pitch}$	excess thrust required of lift engine for pitch control, Newtons (lb)
$\Delta T_{L/C,pitch}$	excess thrust required of lift/cruise engine for pitch control, Newtons (lb)
α	thrust deflection angle in lateral (yaw) direction
$\mathcal{T}_{roll}$	torque required to meet roll maneuver acceleration, N-m lb-ft
$\Delta T_{L,yaw}$	excess thrust required of lift engine for yaw control, Newtons (lb)
$\Delta T_{L/C,yaw}$	excess thrust required of lift/cruise engine for yaw control, Newtons (lb)
$\Delta T_{L,roll}$	excess thrust required of lift engine for roll control, Newtons (lb)
$\Delta T_{L/C,roll}$	excess thrust required of lift/cruise engine for roll control, Newtons (lb)
Teng	engine thrust (eq. (13)), Newtons (lb)

$T_{eng,\ ref}$	reference engine thrust (eq. (13)) , Newtons (lb)
W_{eng}	engine weight (eq. (13)), kg (lb)
$W_{eng,\ ref}$	reference engine weight (eq. (13)), kg (lb)
ε	scaling exponent (eq. (13))

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TABLE I. - RANGE OF VALUES REQUIRED FOR V/STOL

AIRCRAFT MANEUVERING, TRIM AND UPSET

Maneuver, rad/sec^2	Minimum	Maximum
Pitch $\ddot{\theta}$	0.4	0.8
Yaw $\ddot{\psi}$	0.35	0.8
Roll $\ddot{\phi}$	0.8	2.0

(All symbols are defined in the appendix.)

TABLE II. - REPRESENTATIVE VALUES OF MOMENTS OF INERTIA

FOR A TYPE B AIRCRAFT WITH TOGW OF 13 608 KG (30 000 LB)

Control axis	Moment of inertia
Pitch	I_y = 135 580 kg m^2 (100 000 slug ft^2)
Yaw	I_z = 176,250 kg m^2 (130 000 slug ft^2)
Roll	I_x = 18 980 kg m^2 (14 000 slug ft^2)

TABLE III. - LIFT ENGINE EXCESS THRUST REQUIREMENTS FOR ROLL CONTROL

Nominal thrust split, $T_{L/C}/T_L$, %/%	Total lift of L-engine and wing tip jets		Excess L-engine thrust provision for roll control,		
	Newtons	(lb)	Newtons	(lb)	Percent
70/30	40034	9000	11165	2510	27.9
60/40	53379	12000	11165	2510	20.9
50/50	66723	15000	11165	2510	16.7

TABLE IV. - VALUES OF EXCESS THRUST REQUIREMENTS FOR OTHER EFFECTS

		Excess thrust required / TOGW	
(1)	Hot gas reingestion	3.5%	Assumed inlet air $\Delta T = 15^{\circ}$ R
(2)	Suckdown	7.0%	
(3)	Hot day operation	7.0%	90° F day
(4)	Installation losses	7.0%	
(5)	Vertical acceleration	5.0%	Accel. = 0.05 g's
	(Total excess thrust) / (TOGW)	= 29.5%	

TABLE V. - SUMMARY OF EXCESS THRUST REQUIREMENTS

FOR TYPE B AIRCRAFT WITH L PLUS L/C PROPULSION

Type of excess thrust requirement	Excess thrust, % of TOGW
Control:	22-32
Pitch*	22-32
Roll	8.4
Yaw*	6.5-10.5
Other Effects:	
Hot gas reingestion	3.5
Suckdown	7.0
Hot day	7.0
Installation	7.0
Vertical acceleration	5.0
Range of excess thrust required for control: 36.9-50.9%	
Excess thrust required for other effects: 29.5%	
Range of total excess thrust: 66.4-80.4%	

*Ranges of excess thrust for pitch and yaw control are based on a separation between L and L/C engines of 8 to 5 meters (26.3 to 16.4 ft)

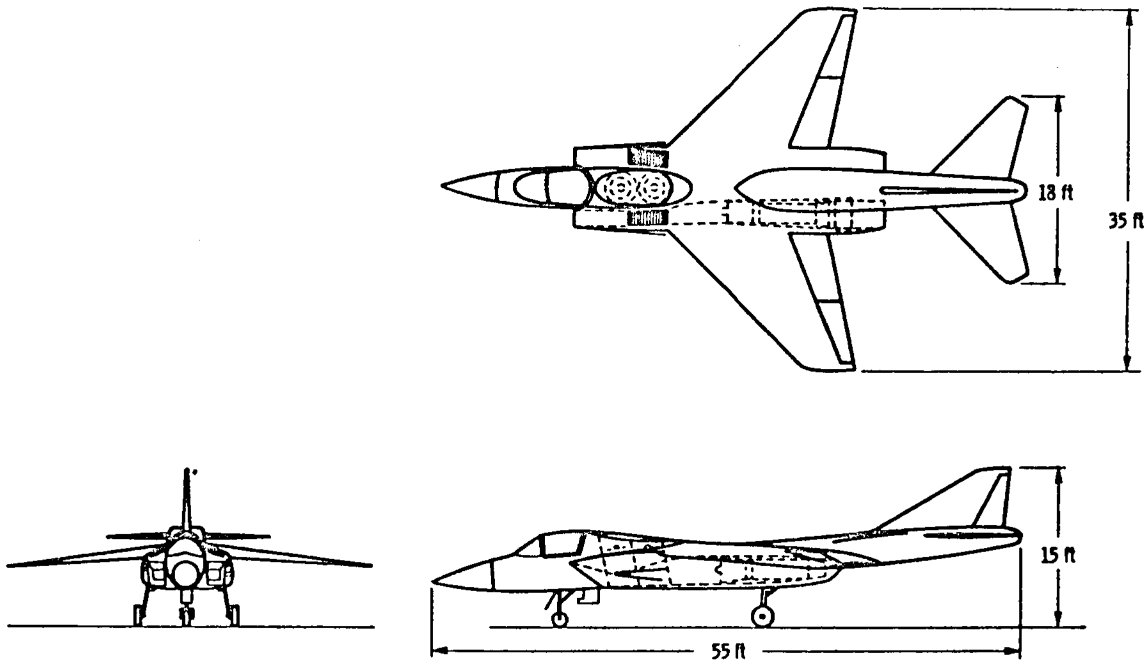
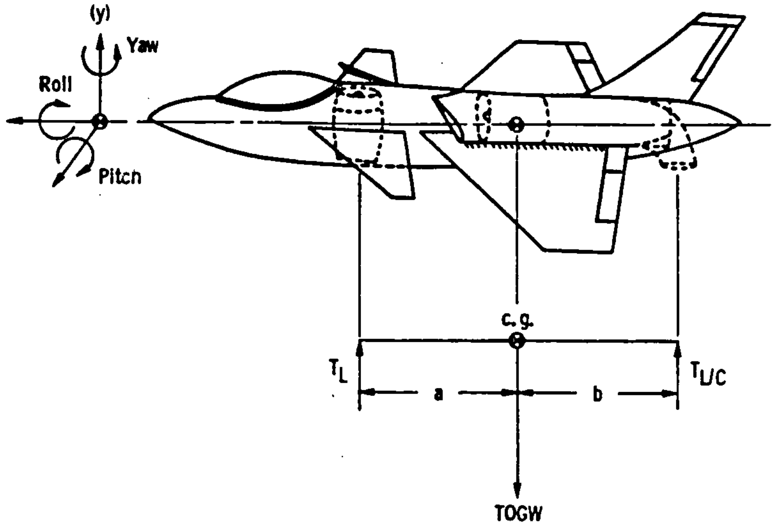


Figure 1. - Sketch of proposed V/STOL, type B aircraft configuration with L + L/C propulsion.



Free-body diagram of forces acting in pitch plane

Figure 2. - Sketch of typical type B aircraft along with free-body diagram of forces acting on aircraft during stationary hover mode of flight.

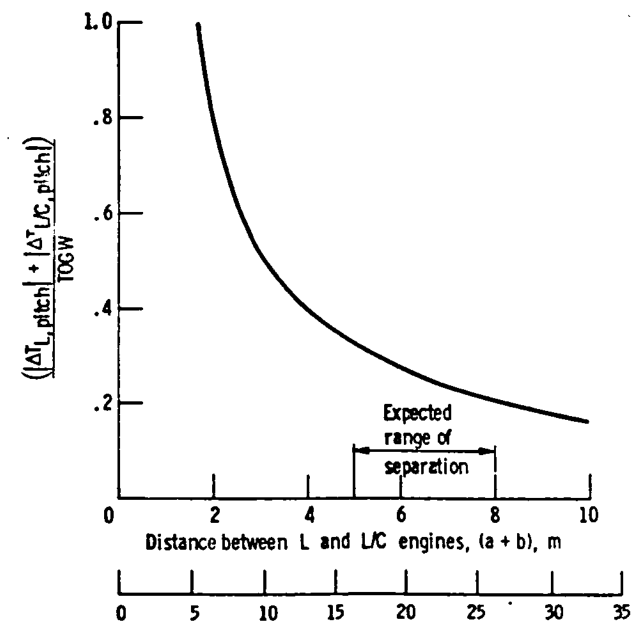


Figure 3. - Excess thrust required for pitch control versus distance between L and L/C engines.

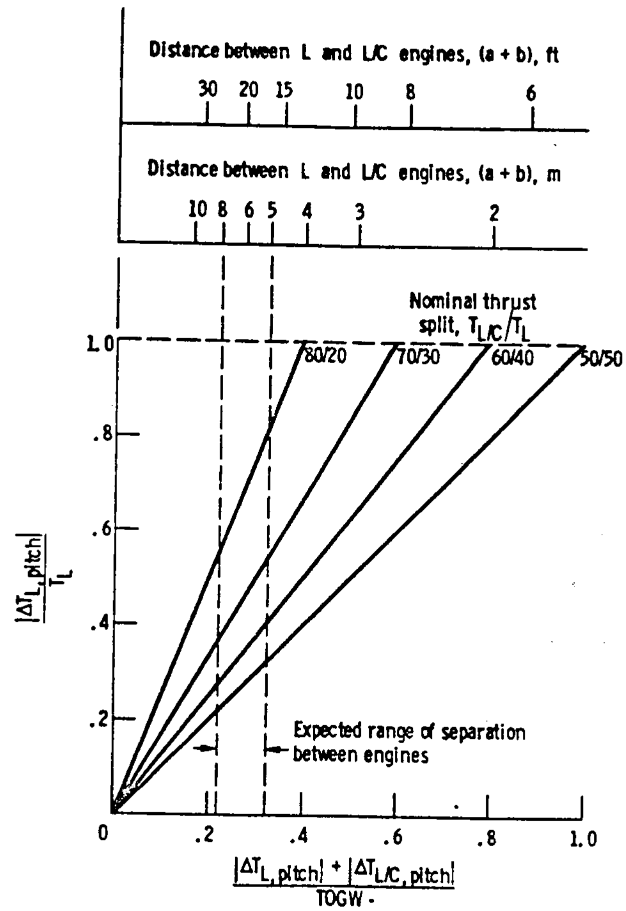


Figure 4. - Relative change in lift engine thrust against total excess thrust required for pitch control for various thrust splits.

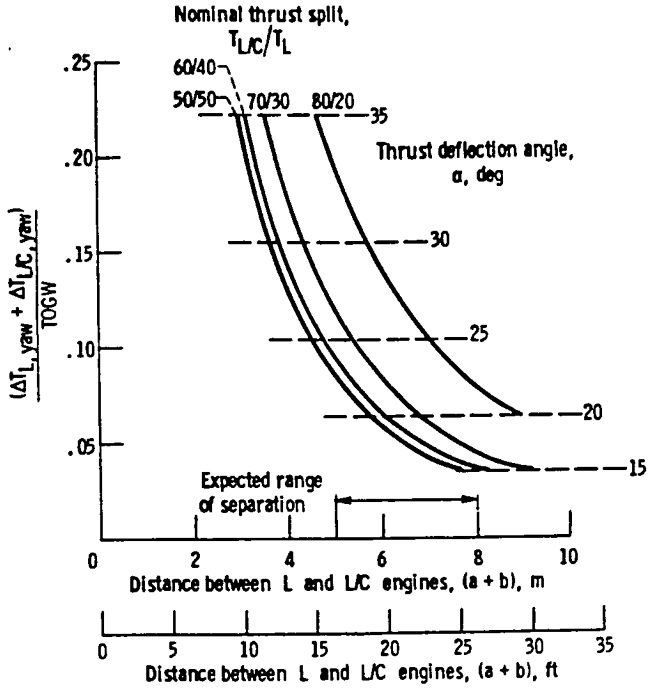


Figure 5. - Excess thrust required for yaw control versus distance between L and L/C engines for various thrust splits and deflection angles.

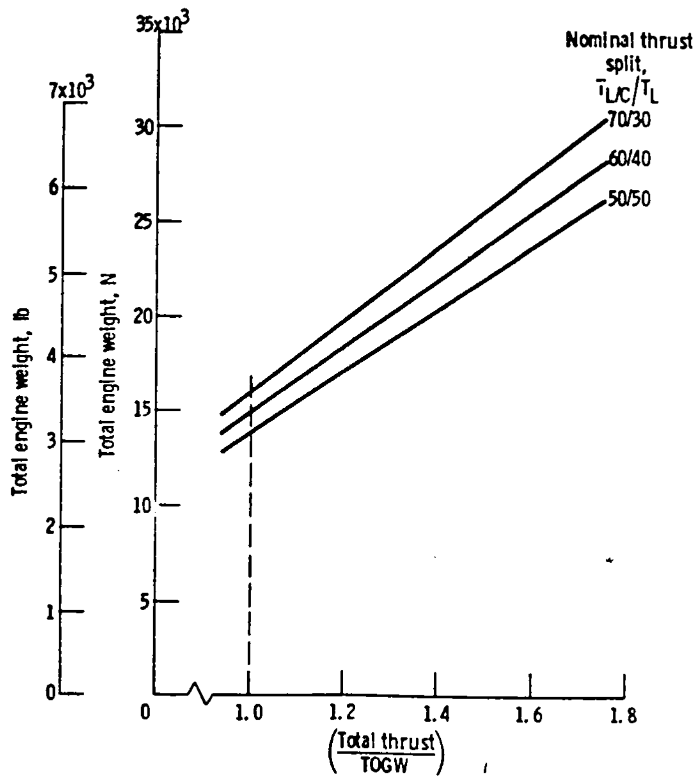


Figure 6. - L + L/C propulsion system weight against propulsion system thrust for different thrust splits.

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16. Abstract

A preliminary assessment was made of the VTO thrust requirements for a supersonic (Type B) aircraft with a Lift plus Lift/Cruise propulsion system. For this study, we assumed a baseline aircraft with a TOGW of 13 608 kg (30 000 lb). Pitch, roll and yaw control thrusts (i.e., the thrusts needed for aircraft attitude control in the flight hover mode) were estimated based on a specified set of maneuver acceleration requirements for V/STOL aircraft. Other effects (such as installation losses, suckdown, reingestion, etc.), which add to the thrust requirements for VTO were also estimated. For the baseline aircraft, the excess thrust required for attitude control of the aircraft during VTO and flight hover was estimated to range from 36.9 to 50.9 percent of the TOGW. And the excess thrust required for the other effects was estimated to be 29.5 percent of the TOGW. It was concluded from this preliminary study that the total thrust requirements for the aircraft/propulsion system are large and significant. In order to achieve the performance expected of this aircraft/propulsion system, reductions must be made in the excess thrust requirements.

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