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METHOD FOR PREDICTION AND DETERMINATION OF TAKEOFF
PERFORMANCE FOR VECTORED THRUST VEHICLES (U)
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METHOD FOR PREDICTION AND DETERMINATION OF TAKEOFF PERFORMANCE FOR VECTORED THRUST VEHICLES

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VSTOL TAKEOFF PERFORMANCE

YAV-8B and AV-8B Short Takeoff (STO) test results had indicated that STO techniques for the Harrier II could be further optimized, particularly for operations at higher hover weight ratios (1.3 and above). This paper documents a method to predict and determine optimum land-based STO performance with minimum flight testing required. The method was applied during the determination of the optimum STO performance of the AV-8B, and is tailored generally toward thrust vectored vehicles with rapid thrust vectoring capability. With certain assumptions accounted for this approach can also be used in less restricted cases. Emphasis was placed on developing a
20.
repeatable task terminating with sufficient flight path acceleration at 50 ft AGL. STO tests
carried out using the revised STO procedures validated the improvement in STO performance.
Changes to the AV-8B flight operations manual were recommended in order to implement the
revised STO task.
SUMMARY

YAV-8B and AV-8B Short Takeoff (STO) test results had indicated that STO techniques for the Harrier II could be further optimized, particularly for operations at higher hover weight ratios (1.3 and above). This paper documents a method to predict and determine optimum land-based STO performance with minimum flight testing required. The method was applied during the determination of the optimum STO performance of the AV-8B, and is tailored generally toward thrust vectored vehicles with rapid thrust vectoring capability. With certain assumptions accounted for this approach can also be used in less restricted cases. Emphasis was placed on developing a repeatable task terminating with sufficient flight path acceleration at 50 ft AGL. STO tests conducted using the revised STO procedures validated the improvement in STO performance. Changes to the AV-8B flight operations manual were recommended in order to implement the revised STO task.
METHOD FOR THE DETERMINATION AND OPTIMIZATION OF VECTORED THRUST TAKEOFF PERFORMANCE

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Abstract

YAV-8B and AV-8B Short Takeoff (STO) test results had indicated that STO techniques for the Harrier II could be further optimized, particularly for operations at higher hover weight ratios (1.3 and above). This paper documents a method to predict and determine optimum takeoff performance with minimum flight testing required. The method was applied during the determination of the optimum STO performance of the AV-8B, and is tailored generally toward thrust vectored vehicles with rapid thrust vectoring capability. With certain assumptions accounted for this approach can also be used in less restricted cases. Emphasis was placed on developing a repeatable task terminating with sufficient flight path acceleration at 50 ft above ground level. Short takeoff tests conducted using the revised STO procedures validated the improvement in STO performance. Changes to the AV-8B flight operations manual were recommended in order to implement the revised STO task.

Nomenclature

Symbol | Description
--- | ---
a | net acceleration
\( (a/g)_D \) | normalized flight path acceleration for aircraft at weight \( W_0 \)
\( (a/g)_L \) | normalized flight path acceleration for aircraft at weight \( W_L \)
\( C_D \) | aircraft drag coefficient
\( C_{LH} \) | lift coefficient in ground effect
\( C_{Dh} \) | drag coefficient in ground effect
\( D_{hy} \) | drag evaluated in ground effect
\( D_m \) | momentum drag (total mass flow rate times vehicle airspeed)
\( F \) | net force acting in the flight path direction
\( F_{L,L,B} \) | average net non-conservative force between \( V_{t0} \) occurring at \( V_t \), \( V_L \), \( V_B \)
\( h_1 \) | height at initial position
\( h_f \) | height at final position
\( \Delta h \) | height or altitude difference between initial and final conditions
\( L \) | average aerodynamic lift evaluated in ground effect
\( L_m \) | total lift (aerodynamic and thrust generated lift)
\( M \) | aircraft mass
\( S \) | average total mass flow rate through engine wing reference area
\( S_{S/G} \) | integral path distance, ground roll distance estimated percent error in ground roll distance due to the instantaneous takeoff assumption
\( S_{G/R} \) | ground roll distance to velocity for thrust vectoring
\( S_{S/G,R} \) | ground roll distance to takeoff
\( S_{A/P} \) | estimated distance from \( V_L \) to \( V_{A/P} \)
\( S_{T/P} \) | air distance traveled along the flight path to 50 ft AGL
\( S_{G/T} \) | ground distance traveled for climbout to 50 ft AGL
\( M \) | aircraft mass
\( \dot{W} \) | mass flow rate of air through the engine installed net thrust,
\( T \) | installed gross thrust,
\( \Delta t \) | time difference between initial and final conditions
\( V \) | airspeed
\( V_{t0} \) | velocity for minimum acceptable a/g
takeoff velocity
\( V_L \) | vertical airspeed
\( V_{e} \) | velocity for engine thrust vectoring to target \( \theta_e \)
during takeoff run
\( V_{n} \) | nozzle rotation velocity (same as \( V_{e} \))
\( W \) | gross weight
\( W_c \) | aircraft weight in climbing flight
\( W_D \) | desired weight for weight correction
\( W_L \) | aircraft weight in level flight
\( W_F \) | gross weight at initial height
\( W_F^* \) | gross weight at final height
\( W/W_h \) | height weight ratio (aircraft weight divided by maximum weight at which the aircraft can hover for given ambient conditions)
\( x \) | aircraft c.g. position
\( \alpha \) | flight path angle without wind correction
\( \gamma \) | flight path angle corrected for wind effects
\( \dot{X} \) | average aircraft ground roll acceleration (evaluated at \( V_{/n}^2 \) if assumed constant)
\( \mu \) | dynamic coefficient of surface friction
\( \theta_e \) | angle between line of thrust and fuselage reference line (thrust vector angle)
\( \rho \) | ambient density
\( \Phi \) | average acceleration from \( V_L \) to \( V_{t0} \)

Introduction

This paper develops and presents an approach to predicting and determining optimum Short Takeoff performance for rapid thrust vectoring vehicles. STO performance refers to velocity and distance required to takeoff, velocity and distance required to clear an obstacle, and the velocity at which thrust is vectoring during ground roll initiating takeoff. Unlike conventional takeoffs, since it is difficult to separate STO testing of vectored thrust aircraft into distinct flying qualities and performance areas. A detailed STO task is directly dependent upon both aircraft performance and STO technique (which includes climbout as well as takeoff). The approach outlined for predicting STO performance involves optimization of the parameters relative to lift, drag, thrust, and flight path acceleration. Optimization also accounts for the requirements for quick and precise attitude capture, attitude control and maximum rate of climb. The developed flight test method for determination of optimum STO performance was applied to the AV-8B Harrier II aircraft. Method and results are presented herein.

Prediction of Short Takeoff Performance

Objective

Basic performance prediction is achieved through a mathematical analysis of the governing equations. STO performance should be optimized for full operational capability within the given performance and handling limitations of the aircraft concerned. By identifying the variables required for STO performance prediction, separation of the variables into...
task dependent and airframe dependent categories can be achieved. The STO task can then be developed accounting for both performance and controllability. It is important to remember that controllability greatly affects the airframe distance required to clear a given obstacle.

**Short Takeoff Profile**

The typical short takeoff profile (figure 1) for rapid thrust vectoring vehicles generally consists of the ground roll phase, a brief thrust rotation-takeoff-position capture phase, and the climb-out-acceleration-transition phase. Vectored thrust minimizes ground roll distance to takeoff by augmenting wing lift with thrust lift. This concept has been adopted for use in certain land based, shipboard, and restricted area operations.

Figure 1 Typical Short Takeoff Profile

**Takeoff Ground Roll Distance Prediction**

Ground roll distance can be predicted by applying the work-energy relationship. For basic terms this relationship states

\[
\int \text{(work)} = \int \text{(energy)}
\]

where \( F \) = non-conservative forces acting on the body

\( \Delta PE \) = change in potential energy from initial state to final state

\( \Delta KE \) = change in kinetic energy from initial state to final state

The forces acting on an aircraft during the takeoff ground roll are shown in figure 2. Applying the work-energy relationship,

\[
\int [T \cos(\theta_j + \alpha) - D - \mu(W - L - T \sin(\theta_j + \alpha))] dS = \frac{W V_j^2}{2g} - W \Delta h
\]

(1)

To reduce the complexity of the integral certain assumptions can be applied. First, assume \( T \) is constant over the ground run, with the constant value taken where velocity is equal to \( V \).

\[
V = \frac{V_j \sqrt{2}}{2} \text{(average between initial and final conditions). This is a valid assumption for jet aircraft during the ground run (reference 1). Second, assume } W \text{ is constant over the ground run. The validity of this assumption depends upon the initial gross weight of the aircraft, the fuel flow required for takeoff thrust rating, and the time required (distance required) to takeoff. Because the velocity vector direction is not changing during the ground roll, assume } \alpha \text{ remains fairly constant over the takeoff ground roll. Since most runways have little or no slope, } \Delta \theta \text{ is negligible, therefore assume } \Delta PE = 0. Fix the thrust vector angle during takeoff at an angle less than 20 degrees relative to the velocity vector during the ground roll and assume that momentum drag and gross thrust are reasonably parallel to the velocity vector (as assumed in figure 1, however for clearness } \theta \text{ is shown out of scale). For aircraft with rapid thrust vector capability, thrust should remain aft for the takeoff ground run in order to maximize acceleration and minimize ground roll distance. At thrust vector rotation velocity, thrust would be vectored such that takeoff would occur rapidly with sufficient flight path acceleration. For slow vector thrust capability (such as tilt rotor aircraft), } \theta \text{ would most likely remain fixed throughout the takeoff. If } \theta \text{ does not remain below 20 degrees, then this assumption that momentum drag and gross thrust are parallel to the velocity vector is no longer valid. In that case, the net thrust term needs to be separated into the momentum drag and gross thrust components such that the momentum drag is accounted for in the direction of the aerodynamic drag and the gross thrust is accounted for in the vectored thrust direction. This differs from conventional takeoff and landing aircraft where the thrust remains fairly parallel with the velocity vector.}

Integrating equation (1) using the above assumptions, and recalling from basic aerodynamics that drag and lift are equal to \( 1/2 p V^2 \sqrt{CD} \) and \( 1/2 p V^2 \sqrt{CL} \), respectively, the following equation for ground roll distance to takeoff is obtained:

\[
S = \left[ \frac{1}{W} \left( \frac{pgs}{s} + (\frac{C_L}{s} - C_D) \right) \right] T/L + \frac{V_j \sqrt{2}}{2(W)} + \frac{1}{2p} \sqrt{2g} + \frac{1}{2p} \sqrt{2g}
\]

(2)

Equation (2) additionally assumes takeoff occurs rapidly after thrust vectoring. A good estimate for time between \( V \) to \( V_j \) obtained from flight test is approximately 1 sec for 20,000 to 30,000 lb rapid thrust vectored jet aircraft. The difference in takeoff distance resulting from the instantaneous takeoff assumption can be surveyed in order to determine the validity of this assumption for a given case.

Aircraft acceleration will decrease upon thrust vectoring mostly due to the reduction in thrust acting in the axial direction. Acceleration may also decrease if high lift devices (such as flaps) are scheduled to react with the vectored thrust (due to the increase in induced drag). In cases where vectored thrust is used in conjunction with high lift devices (such as flaps), the influences of thrust on \( C_D \) and \( C_L \) must also be accounted for. Aircraft acceleration changes between initiation of thrust vectoring and takeoff can be estimated from

\[
\phi = \left( V_j - V \right) / \Delta t = V \Delta t / \Delta v
\]

(3)

Using \( \Delta t = 1 \) sec, and assuming ground roll acceleration (A) is constant, equation (3) can be rearranged and integrated to obtain

\[
S = \int [V_j - V] \sqrt{2/(V_j - V)}
\]

(4)

The error associated with the instantaneous takeoff assumption \( (S = S_j) \) can be estimated using

\[
S_e(\%) = \frac{S_j}{(S + S_j) + 100}
\]

(5)

Constant ground roll acceleration can be determined from

\[
A = \int [T \cos(\theta_j + \alpha) - D - \mu(W - L - T \sin(\theta_j + \alpha))] / (g/W)
\]

(6)

The assumption of constant ground roll acceleration does not necessarily over simplify the ground roll distance equation. Variation of forces acting on the aircraft during ground run are shown in figure 3. With low takeoff velocities associated STO operations, assume net thrust will remain reasonably constant over the ground run (minimum change in T due to a change in
momentum drag over the ground run). As lift develops, drag increases and \(\mu(W - L - T \sin (\theta_1 + \alpha))\) decreases. Even though these forces cannot be shown to directly cancel, the net difference in these forces will remain reasonably constant during the takeoff, particularly for short takeoff distances. As in the constant thrust assumption, \(A\) should be calculated at conditions where the velocity is equal to \(V_{to}/V^2\).

Figure 3 Variation Of Forces During Ground Roll

Flight test takeoff data obtained from Harrier STO testing supports the validity of the constant ground roll acceleration assumption. Assuming the ideal case where gross thrust is the only force acting on the aircraft during the ground run in the direction of the velocity vector, the work-energy expression becomes

\[
1/2(W/g)V^2 = T_f \cdot S_d = (W/g) \cdot a \cdot S_d
\]

By rearranging the terms, the expression becomes

\[
a = 1/2(V^2/S_d)
\]

Therefore, the acceleration is linearly proportional to \(V^2/S_d\). Multiplying both sides of the equation by \(W/g\) and rearranging the terms gives

\[
2gS_d = (W/T_{le}) \cdot V^2
\]

The term \((W/T_{le}) \cdot V^2\) is commonly referred to as the acceleration parameter. \(W/T_e\) can be replaced by hover weight ratio, \(WW_h\). Hover weight, \(W_h\), is defined as the maximum weight at which the aircraft can remain in a steady hover over the ground roll distance. As lift develops, drag mostly increases to the significant increase in aerodynamic drag resulting from the higher takeoff velocities required for the lift necessary to offset the higher gross weights. The effect also occurs as a result of increased momentum drag. At the point of degrading linearity, the constant ground roll acceleration assumption becomes less valid.

Figure 4 Ground Roll Acceleration Curve

Using the constant \(A\) assumption, equation (1) can be integrated and rearranged to become

\[
S_d = V_{to}^2/(2A)
\]

Again, this assumes takeoff occurs quickly after thrust vectoring. However, equation (4) can be used to estimate \(S_d\). The advantage of equation (7) is that \(S_d\) can be analyzed relative to \(A\), thus determining the effects of different accelerations on ground roll distance. As will be shown, this becomes more useful for the air distance equation.

Variation Of Lift And Drag With Ground Roll Distance

For analysis purposes, \(L\) and \(D\) can be expressed as a function of \(S_d\). The rate of change of drag with ground roll distance can be expressed as

\[
dD/dS_d = (dV/dV/dt)(dS_d/dt)
\]

Substituting in,

\[
dD/dV = dV/(1/2pV^2SC_{D_S}) = pVSC_{D_S}\]

simplifies to

\[
dD/dS_d = pVSC_{D_S} [(T \cos (\theta_1 + \alpha) - D_s) \cdot \mu(W - L - T \sin (\theta_1 + \alpha))]/(g/W)
\]

Relationships of the variables in \(dV/dt\) to \(S_d\) can be substituted in for best results. A more simplified version can be obtained by assuming \(C_L\), \(C_D\), and \(W\) remain constant over the ground run, and using the constant \(A\) assumption. Integrating with respect to ground roll distance gives the following:

\[
D(S_d) = pV^2C_{D_S}S_d
\]

Knowing \(L = 1/2pV^2C_{L_S}\), a similar approach yields

\[
L(S_d) = pV^2C_{L_S}S_d
\]

Determination Of Velocity For Thrust Vectoring

In theory takeoff occurs when the total lift is equal to the aircraft weight \(W = L_t\). Therefore \(V_{to}\) would be the velocity corresponding to the point where

\[
L_t = 1/2pV_{to}^2C_{L_S} + T \sin (\theta_1 + \alpha)
\]
for some given \( T_e \) resulting from a takeoff power throttle setting. Because thrust vector angles used for takeoff will be large, the net thrust term is broken into the gross thrust and momentum drag terms due to the respective differences relative to the flight path. For drag bookkeeping purposes, momentum drag is commonly resolved in the direction of the velocity vector (perpendicular to \( L_b \)).

Takeoff velocity for determining the ratio of wing lift to thrust lift is very important. If minimum wingborne lift is used, a larger \( \theta \), is required, thus allowing less thrust for acceleration during transition from semijetborne flight (flight requiring both aerodynamic and thrust generated lift) to wingborne flight (flight requiring aerodynamic lift only) during climbout. Also, if takeoff velocity is such that maximum lift available from the wing is required for \( W = L_b \), angle of attack will be large creating additional induced drag and a potential stall hazard. Therefore, the balance of wing lift and thrust lift is critical not only for takeoff, but for climbout characteristics as well.

The key to STOL operations is not necessarily to takeoff in the minimum distance required, but to takeoff and climb out above some height in the least possible distance while maintaining adequate flight path acceleration for containing the climb to desired altitude. If the wing lift to thrust lift ratio is not optimum for the STO technique, the pilot may takeoff in the minimum distance required, but he may significantly increase that distance trying to accelerate and climb above an obstacle. The STO technique also has a direct impact in optimizing the STO task for minimum distance required to clear a given height -1. maintaining a reasonable flight path acceleration. Another variable impacting STO performance is engine operating limitations (temperature, RPM, etc.). Takeoff velocity should allow flight path acceleration to minimize the time required to adequately perform the STO task such that engine life is not reduced and/or thrust reduction does not occur due to reaching or exceeding engine operating limits during climbout and transition to wingborne flight.

The velocity at which a pilot vectors thrust in order to initiate takeoff is \( V_\alpha \). Assumptions can be made to simplify equation (10) allowing the development of a thrust vector velocity schedule relating takeoff velocity with thrust available, thrust vector angle, and gross weight for some predetermined STO technique. Substituting in \( L_b \geq W \) at takeoff, replacing \( W/T_g \) with \( W/W_{\alpha} \) and rearranging the terms gives

\[
(V/W) \geq \sqrt{(1 - \frac{W}{W_{\alpha}}) \sin(\theta + \alpha)} / (\rho S C_{L_b})
\]  

(11)

The term \( V/W \) is termed the velocity parameter. Equation (11) shows that velocity parameter is a function of only hover weight ratio for a given STO technique where thrust is vectored to the same \( \theta \), and \( \alpha \) at takeoff is consistent for all gross weights (i.e., target \( \theta \), and \( \alpha \) are a result of the STO technique). From this, a schedule depicting velocity for thrust vectoring can be estimated and presented as \( V/W \) versus \( W/W_{\alpha} \) as shown in figure 5. If takeoff was assumed to occur at the instant that thrust was vectored, \( V_\alpha \) could be replaced with \( V_{\text{to}} \). However, recall that the determination of the takeoff velocity (a direct relation with \( V_{\text{to}} \)) is a function of the STO technique as well as the lift and thrust performance of the aircraft. While addressing constraints due to the STO technique, equation (11) can be used to estimate a takeoff schedule prior to actual STO testing.

If the STO technique is an attitude takeoff task (i.e., thrust is vectored at \( V_{\alpha} \) and takeoff occurs shortly afterwards without rotation of the nose (as is usually required with conventional takeoff aircraft)), then ground run pitch attitude can be substituted into equation (11) for \( \alpha \).

Prediction of Ground Distance Required to Clear An Object During Takeoff Air Phase

In order to determine the total distance required to clear an obstacle during a STO, the air phase distance must be accounted for separately from the ground roll phase distance due to the difference in the forces acting on the aircraft.

The free body diagram for an aircraft in flight is shown in figure 6. Applying the work-energy relationship gives the following expression

\[
(W/g) \int V dV
\]  

(12)

The subscript 1 defines the datum at the takeoff position as 0, and the subscript 2 is at 50 ft AGL level. If the weight change between takeoff and 50 ft AGL is assumed negligible, then gross weight is a constant.

Applying this assumption, equation (12) can be simplified to

\[
(W/g) \int V dV = (W/(2g))(V^2_{50} - V^2_0 - 100g)
\]  

(13)

Ideally, for the determination of flight path distance \( (S_d) \) required to clear 50 ft AGL, relationships of \( D_m, \theta \), and \( \alpha \) to \( S_d \) between takeoff and 50 ft AGL would be required for solving equation (13). These variables are directly related to flight path acceleration, and are therefore crucial relative to STO performance optimization.

As shown for the ground roll case, certain assumptions can be applied to equation (13) in order to develop a more simplified form. Because the optimization of STO performance will result in low, but acceptable flight path acceleration, and as a result of the position capture climbout task during the air phase portion of the STO, assume \( \alpha, C_\text{p} \), and \( D_m \) remain fairly constant over the climbout to 50 ft AGL. Also, assume that \( T_g \) will not vary during climbout. Furthermore, assume that the thrust vector angle is constant throughout the climbout. If acceleration is adequate, the pilot may begin to vector the thrust aft and transition to wingborne flight prior to 50 ft AGL. Relative to available flight path acceleration for the given climbout angle, the constant \( \theta \), assumption during climbout is the worse case situation. However, if the pilot transitions to wingborne flight too soon, the aircraft could begin to descend due to the deviation from optimum \( L_b \) conditions.

Since all the variables within the integral are assumed to be fairly constant throughout the climb, the non-conservative forces are now presented as

\[
F_{\text{avg}} = (T_g \cos(\theta + \alpha)) \cdot D_m / V_{\text{avg}}^2
\]

As in the ground roll equation, the parameters assumed to be constant over the air phase should be evaluated at average conditions occurring at \( V(V_0^2 + V_{50}^2)/2 \). Integrating and rearranging equation (13) gives the following expression
The ground distance covered during climbout is

\[ S_{dp} = (W/(2gF_{avg}))(V_{So}^2 - V_u^2 - 100g) \]  

Therefore, the ground distance covered during climbout is

\[ S_{dp} = S_p \cos \gamma_g \]  

For no wind conditions, the angle \( \gamma_g \) can be calculated from

\[ \arcsin (V/V_o) = \gamma_g \]  

Applying equation (15) to equation (14), the following is obtained:

\[ S_{dp} = (W/(2gF_{avg}))(V_{So}^2 - V_u^2 - 100g) \cos \gamma_g \]  

The simplified version of the air phase distance equation is a relationship, they assume that airspeed is equal to inertial ground acceleration (\( a_g \) required to clear climbout.

Because the equations predicting takeoff distance and distance required to clear climbout. Therefore, the only difference between equations (20) and (23) lift can be expressed as

\[ \frac{V_c \cos \theta - \alpha}{\cos \gamma} \cdot \frac{L + W_c \cos \gamma \cdot T_e \sin \theta - \alpha}{(2/L) \cos \gamma} \]  

Rearranging and solving for \( \tan \gamma \) gives

\[ \tan \gamma = \left( \frac{T_e \cos \theta - \alpha}{\tan \gamma} \cdot \frac{L + W_c \cos \gamma \cdot T_e \sin \theta - \alpha}{(2/L) \cos \gamma} \right)^{1/2} \]  

Note that \( D/L \) can be replaced by \( C_D \cdot C_L \)

Summing the forces along the flight path for a level acceleration (\( \gamma = 0 \) ) gives

\[ \Sigma F_x = T_e \cos (\theta - \alpha) \cdot D \cdot D_{ML} = (W/L) \tan \gamma \cdot \alpha_{ML} \]  

\[ \Sigma F_y = T_e \sin (\theta - \alpha) + L \cdot W_c \cos \gamma \cdot T_e \sin (\theta - \alpha) \]  

Therefore,

\[ D/L = \left( \frac{T_e \cos (\theta - \alpha) - W_c \sin \gamma \cdot D_{ML}}{W_c \cos \gamma \cdot T_e \sin (\theta - \alpha)} \right) \]  

Because the lift and drag are different for climb and level flight, the relationship between the climb velocity and level flight velocity needs to be established in order to determine the velocity associated with the level flight \( a/g \). From equations (19) and (22) lift can be expressed as

\[ L_c = \frac{W_c \cos \gamma \cdot T_e \sin (\theta - \alpha)}{C_{Lc}} = \frac{(1/2)pV^2S_c \cdot Lc}{C_{Lc}} \]  

So for \( W_c = W_c \cos \gamma \), and assuming \( p, T_e, \theta \), and \( S \) to be the same for both the climb and level flight situation, then

\[ L_c = L_c \cdot C_{Lc} \cdot \text{Therefore,} \]  

\[ C_{Lc} = C_{Lc} \cdot \text{Therefore,} \]  

\[ \alpha_c = \alpha_c \cdot \text{Therefore,} \]  

\[ V_c = V_c \cdot \text{Therefore,} \]  

\[ D_c = D_c \cdot \text{Therefore,} \]  

\[ \frac{(5/2)10^3}{20^2} \cdot C_{Lc} \cdot \text{Therefore,} \]  

\[ D_{MC} = D_{ML} \cdot \text{Therefore,} \]  

Thus, the only difference between equations (20) and (23) of the equal sign is the aircraft gross weight term in the divisor. The flight path angle obtained during constant airspeed climb tests can be related to level flight acceleration if \( W_c = W_c \cos \gamma \). The relation can be written by

\[ \tan \gamma = \frac{a/g}{W_c \cos \gamma} \]  

where \( W_c = W_c \cos \gamma \), and the flight path angle \( \gamma \) during the climb test is determined from

\[ \text{arcsin} \left( \frac{V_c}{V_o} \right) = \text{arcsin} \left( \frac{(\Delta V/\Delta t)V_o}{(\Delta V/\Delta t)W_c} \right) = \gamma \]  

Equation (24) states that the flight path acceleration of an aircraft in level flight at weight \( W_c \), and velocity \( V_c \) can be determined from constant airspeed climb data for which \( V_c = V_c \), and weight \( W_c \) is such that \( W_c = W_c \cos \gamma \). Also, equations (23) and (24) can be used for the development and prediction of the thrust rotation velocity schedule. Note, since drag in level flight is higher than drag in climbing flight for similar aircraft at the same weight and velocity, the \( a/g \) calculated is a conservative estimate of \( a/g \) during climbout at the corresponding velocity.

The calculated level acceleration data can be adjusted for different gross weights. Acceleration correct on, \( a/g \), due to...
weight correction, \( \Delta W \), can be written as

\[
\Delta W = W_D - W_L,
\]

\[
\Delta (a/g) = \left[ (a/g)_D - (a/g)_L \right]_{0}^{N} \tag{24}
\]

Therefore,

\[
\Delta (a/g) = \left[ \left( f(T, \cos (\theta + \alpha)) + (D/L)_{T_s} \sin (\theta + \alpha) - D_{M} \right) / W - \left( f(T, \cos (\theta + \alpha)) + (D/L)_{T_s} \sin (\theta + \alpha) - D_{M} \right) / W \right]_{0}^{N} \tag{26}
\]

Constant airspeed climbs at different weights have different angles of attack and momentum drag at the same thrust setting. If weight corrections are small (\( \pm 5\% \)), then it is not unreasonable to assume that the angles of attack for the given desired weight conditions are equal. Therefore, \( V_{D} \) is assumed approximately equal to \( V_{L} \); consequently, \( (D/L)_{T_s} \) is approximately equal to \( (D/L)_{T_s} \) and \( (D/L)_{0} \) is approximately equal to \( (D/L)_{0} \). Although the desired weight condition has the same angle of attack, thrust setting, and approximately the same velocity as the original condition, an algebraic difference in \( a/g \) results because the relative pitch attitude changes due to the difference in weight (i.e., because pitch attitude is equal to the sum of \( \alpha \) and \( \gamma \), the different pitch attitude produces a change in \( \gamma \), which in turn changes \( a/g \)). Applying the above assumptions to equation (26),

\[
\Delta (a/g) = \left[ \left( f(T, \cos (\theta + \alpha)) + (D/L)_{T_s} \sin (\theta + \alpha) - D_{M} \right) / W - \left( f(T, \cos (\theta + \alpha)) + (D/L)_{T_s} \sin (\theta + \alpha) - D_{M} \right) / W \right]_{0}^{N} \tag{27}
\]

Recall again that \( D/L \) can be written as \( D_{L}/C_{D} \). Note also that some cases may constitute a further simplification of equation (27) to

\[
\Delta (a/g) = T_{g} \left[ (W_{D} - W_{L})/(W_{D} W_{L}) \right] + (\cos (\theta + \alpha)) + (D/L)_{T_s} \sin (\theta + \alpha) \tag{28}
\]

The difference between \( V_{D} \) and \( V_{L} \) (resulting from the weight change and constant angle of attack assumption) can be calculated. Solving equation (19) for \( T_{g} \), substituting into equation (18), rearranging the expression and applying the assumptions used in developing equation (24) shows

\[
V_{L} = \left[ (W_{L} - 1 - \tan (\theta + \alpha)) \right. - D_{M} \tan (\theta + \alpha)] / ((C_{D} \sin (\theta + \alpha)) + C_{L}) + (1/2) p S = V_{C} \tag{29}
\]

Dividing equation (28) by equation (29) and applying equation (24) produces

\[
\left( V_{D} / V_{L} \right)^{2} = \left[ (W_{L} - 1 - \tan (\theta + \alpha)) \right. - D_{M} \tan (\theta + \alpha)] / ((C_{D} \sin (\theta + \alpha)) + C_{L}) + (1/2) p S \tag{30}
\]

Applying the previous assumptions valid for a small weight correction allows

\[
1 = \left[ (W_{D} - 1 - \tan (\theta + \alpha)) \right. - D_{M} \tan (\theta + \alpha)] / \left[ (W_{L} - 1 - \tan (\theta + \alpha)) \right. - D_{M} \tan (\theta + \alpha)] \tag{31}
\]

Therefore,

\[
V_{D} = V_{L} \left[ (W_{L} / W_{D}) \right] = V_{C} \left[ (W_{L} / W_{C}) \cos (\gamma) \right] \tag{32}
\]

The variables used to express \( a/g \) can be collected as independent, non-dimensional parameters in order to better evaluate aircraft performance. From equation (23)

\[
a = f(T_{g}, \theta, \alpha, g, D/L, D_{M}, W) \tag{33}
\]
For this case, W varies only with the fuel state of the vehicle. The non-dimensional parameter, \(x_1\), can be rearranged using x = f(W) by substituting in m for x, noting that g is already accounted for, such that the dimensional velocity parameter (previously defined) is obtained as:

\[ x_1 = \frac{V_L}{W_L} \]

Therefore, a/g can be expressed as:

\[ a/g = \frac{f(W/L/T_e)}{V_L/(W/L)} \]

Assuming changes in \(D_n/T_e\) to be negligible over the range of velocities involved, the expression can be further reduced to:

\[ a/g = \frac{f(W/L)}{V_L/(W/L)} \]

Therefore, a/g is primarily a function of thrust to weight ratio and velocity parameter. For a given minimum acceptable a/g and recalling the concept of the hover weight ratio, equation (37) can be written as:

\[ (V_{a/g}) = f(W/T_e) = f(W/W_0) \]

Setting the Kollsman window of the test altimeter to 29.92 in Hg prior to constant airspeed climb tests allows obtaining the standard day graph of \(V_{a/g}/W\) versus a/g from test day data of \(V_{a/g}/W\) versus a/g plotted in terms of test day equivalent airspeed. Variations in a/g due to changes in engine thrust resulting from ambient temperature and pressure effects are accounted for due to plotting a/g data relative to W/W_0. As usual, for best results tests should be performed as close to desired conditions (temperature, pressure, weight, etc.) as possible.

**Relationship of Climbout Task With STO Performance**

Earlier, equation (11) showed that takeoff velocity was related to the STO task by:

\[ (V_{a/g}/W) \geq \sqrt{(2(1 - [1/(W/W_0)]) - [\sin(\theta_1 + \alpha)]/\langle pS_{CL_4} \rangle}) \]  

For a given optimum STO technique, equation (11) becomes:

\[ (V_{a/g}/W) = f(W/W_0) \]

Using equation (19), lift during the climbout phase of the STO is expressed as:

\[ L = (W/g) \cdot a_{so} + Wcos \gamma \cdot T_e \cdot \sin(\theta_2 + \alpha) = (1/2)pV^2S_{CL_L} \]

By rearranging the terms and substituting in W/W_0, the velocity during the climbout task can be expressed as:

\[ (V_{a/g}/W) \geq \sqrt{(2(1 - [a_{so}/g + cos \gamma]) - [\sin(\theta_1 + \alpha)]/\langle pS_{CL_4} \rangle)} \]

The STO task profile defined climbout at a constant attitude or AOA, and in the case of constant attitude climbout, \(\alpha\) is assumed to remain fairly constant. As assumed in the development of equation (14), \(\theta_2\) is constant during climbout. Because the climbout phase of the STO task is relative to clearing an obstacle of reasonably low height (less than 100 ft), density altitude is assumed to remain constant over the climbout. Also, since STO performance is to be optimized within minimum acceptable a/g, assume \((a_{so}/g + cos \gamma) = 1\). Therefore, velocity required for the climbout task can be expressed as:

\[ (V_{a/g}/W) = f(W/W_0) \]

**Optimum STO Performance**

**Prediction**

As discussed earlier, optimum STO performance is governed by minimum acceptable a/g available during the STO task. Equations (39) and (41) formulate the approach to optimizing STO performance, and determining W/W_0 for which a/g becomes unacceptable.

To maximize STO performance, an engineer can manipulate and fix the key variables in equations (4), (7), (11), (17), (23) and (40) as necessary in order to gain in the development of the initial thrust vector velocity schedule for optimum STO performance. Equations (2) and (13) could then be used to predict the associated distance performance. Again, recall that STO performance is directly influenced by handling qualities as well. Therefore, the variables in the above mentioned equations would also be constrained by the requirements of the STO task (i.e., adequate acceleration for climbout, task repeatability, reduced complexity, and minimum pilot workload). The average pilot must be able to execute the STO task with consistent results without the complexity of the task being overwhelming. When the variable combinations of the derived takeoff equations are set such that maximum STO performance is achieved relative to the chosen STO technique, predicted STO performance is considered optimized.

However, the variable combinations for optimum performance will change with W/W_0. In order to reduce the complexity involved in optimizing performance for every possible condition, the STO task is designed along with the constraining variables for operational conditions most likely encountered during the mission of the vehicle. For off-design conditions, the task remains constant (reducing operational complexity) until performance degrades below acceptable conditions. At this condition, selected parameters pertaining directly to vehicle performance can be varied in order to maintain the best possible STO performance for the determined STO task. Because the vehicle is performance constrained by the engine and aerodynamically constrained by geometry, off-design performance can be optimized by changing the target engine thrust vector angle. In order to optimize aircraft handling qualities, longitudinal trim setting for takeoff is varied to obtain the best aircraft response for quick takeoff upon thrust vectoring, and precise attitude targeting and control during climbout.

**Determination**

Unlike conventional takeoff testing, it is difficult to separate STO testing of vectored thrust aircraft into distinct flying qualities and performance tests. The repeatable STO task is directly dependent upon both aircraft performance and STO technique (which includes climbout as well as takeoff). In order to achieve repeatability of optimum STO performance, the STO task must optimize aircraft performance relative to lift, drag, thrust and acceleration, and at the same time balance in the requirements of quick and precise attitude capture, attitude control and maximum available rate of climb.

Constant airspeed climb tests are performed at a given thrust vector angle to obtain plots of velocity parameter versus a/g for various lines of constant hover weight ratio (figure 7). The velocity parameter at which the minimum acceptable a/g occurs is then cross plotted against W/W_0 (figure 8). This plot is then overlaid onto a plot of velocity parameter required during climbout at the captured attitude or AOA versus W/W_0, obtained for the same target thrust vector angle as used during the constant airspeed climb tests (figure 9). The curve depicting velocity parameter required for the climbout task and the velocity parameter for minimum acceptable a/g intersect at a W/W_0 within the operational hover weight ratio envelope.
acceleration is no longer acceptable for the given optimum STO technique utilizing that target thrust vector rotation angle. The hover weight ratio at which the velocity parameter for minimum acceptable a/g equals the velocity parameter required for the climbout task is defined as the thrust vector angle crossover point. If desired, a safety buffer can be utilized in the determination of the thrust vector angle crossover point as shown in Figure 9.

The initial (theoretically predicted) schedule for thrust vector rotation velocity can be compared to the velocity required for minimum acceptable a/g (obtained from flight test). Predicted \( V_{\text{T}} \) should be scheduled to occur at or above the velocity for acceptable level flight path acceleration such that the vehicle has adequate energy for transition to wingborne flight during climbout (thus minimizing ground distance required). If the initial schedule satisfies these criteria, it could be used as the starting point for determination of the final schedule from flight test. Depending on the confidence in the development of the initial schedule, it may be desired to add a safety buffer of 5 to 10 knots to the initial schedule prior to flight testing. Since maximum STO performance is desired, the final schedule for thrust vector rotation velocity should be approximately the same as curve depicting the velocity required for minimum acceptable a/g.

Application Of Technique

Background

YAV-8B and AV-8B STO test results had indicated that the STO performance could be further optimized, particularly at higher hover weight ratios (1.3 and above). Fleet comments and earlier STO test results confirmed the need for land based AV-8B STO performance optimization. STO optimization required the development of a new nozzle rotation schedule and STO task.

Description Of Test Aircraft

This above technique was applied for the determination of optimum STO performance of the AV-8B Harrier II aircraft. The AV-8B is a single place, single engine, tactical attack vectored thrust V/STOL aircraft. The aircraft has a shoulder mounted supercritical swept wing, a single row of auxiliary engine air inlets, four rotatable engine exhaust nozzles, and a Lift Improvement Device System. The AV-8B is powered by a Rolls Royce F402-RR-406 twin spool, axial flow turbofan engine with an uninstalled sea level static short lift wet (water injection) thrust rating of 21,500 lb. The primary flight control system is hydromechanical with a limited authority digital stability augmentation and attitude hold system incorporating a departure resistance system. The Harmer also incorporates a reaction control system providing engine bleed air to puffer duct valves located on the nose, tail and wingtips for longitudinal, lateral and directional control during vectored thrust operations. The engine is equipped with a digital engine control system with a manual fuel system provided for back-up fuel control.

Test Approach

In order to achieve optimization, the STO task was changed to a pitch attitude capture task as opposed to the previous AOA task, and the target thrust vector angle (defined as nozzle
rotation angle, \( \theta \) when used in reference to the AV-8B) was scheduled as a function of the hover weight ratio as opposed to being constant at 55 deg for all \( W/W_h \). Constant airspeed climb tests were performed in order to determine the relationship between hover weight ratio and optimum nozzle angle during the STO task. This allowed the development of a new schedule for the velocity at which nozzles would be rotated \( (V_{ny}) \).

In order to maintain adequate flight path acceleration during high hover weight ratio STO tasks, the target nozzle angle was reduced, resulting in a slight increase in \( V_{ny} \). The reduced nozzle angle increased flight path acceleration, while the increased \( V_{ny} \) provided more wing lift to supplement the reduced thrust lift (resulting from the reduction in nozzle angle).

The new optimum STO performance task outlined the STO task as rotating nozzles at \( V_{ny} \) (obtained from the developed \( V_{ny} \) schedule) to optimum target nozzle angle, capturing 14 deg pitch attitude within 1.5 sec of takeoff, and climbing through 50 AGL within minimum ground distance. Emphasis was placed on a repeatable STO task ending with sufficient acceleration at 50 ft AGL. Stabilator trim, drag and stability effects of stores, flight path acceleration, and flying qualities were all considered in the development of the revised nozzle rotation schedule. A new stabilator trim schedule was developed to enhance the pitch capture task in order to promote repeatability of the STO task. The schedule needed to account for the stability effects of stores, e.g. position, and potential reaction control system induced foreign object debris engine damage.

The STO task originally dictated application of the longitudinal stick as necessary to reach and maintain 12 units AOA after nozzle rotation and takeoff. However, previous test results showed that a reduction in flight path angle was required to maintain positive longitudinal flight path acceleration. Further testing was recommended in order to determine the optimum AOA for STO climbout. However, during the AV-8B Navy Technical Evaluation, it was determined that STO tasks capturing pitch attitude with proper trim were easier than capturing AOA due to the lag in the AOA indication in the HUD, and the tendency for the pilot to induce oscillations in AOA when targeting an AOA for climbout. Target pitch angle was chosen in order to optimize climbout AOA during higher hover weight ratio STO operations, as well as to maintain similarity with shipboard STO procedures.

Both the optimum and original STO tasks outlined STO procedures as initially setting proper control surface trim, selecting proper flap setting, selecting proper weight angle setting for the ground roll, applying appropriate power with brakes applied, releasing brakes at initial skid, accelerating to target \( V_{ny} \), rotating nozzle lever to the pre-selected nozzle angle STO stop, and performing an attitude takeoff task. The main difference in task technique lies in capturing 14 deg pitch attitude within 1.5 sec for the optimum task as opposed to capturing 12 deg AOA for the original task. The tasks also have different \( V_{ny} \), \( \theta \), and stabilator trim schedules. Both tasks call for maintaining altitude and heading during climbout.

**Test Method**

In order to determine the optimum nozzle rotation schedule, tests were conducted in two phases. The first phase involved the determination of the nozzle crossover point (the hover weight ratio for which the velocity parameter for minimum acceptable \( a/g \) equals the velocity parameter required for the 14 deg pitch attitude climbout task). The nozzle crossover point was determined by flying constant airspeed sawtooth climbs at various hover weight ratios for 50 deg and 55 deg nozzle angles. Low pressure fan speed RPM was set during the climb in order to generate the required thrust for the targeted hover weight ratio. Constant airspeed climb data was then used to determine the velocity required to maintain a 14 deg pitch attitude and the velocity for minimum acceptable \( a/g \). From experience gained during shipboard trials, the minimum acceptable \( a/g \) was chosen to be 0.04 g. During STO tests 0.04 g was again confirmed to be the minimum acceptable flight path acceleration for STO operations. The nozzle angle crossover point was determined from the intersection of the curves depicting velocity parameter required for 14 deg pitch attitude climb and velocity parameter for minimum acceptable \( a/g \) as a function of \( W/W_h \) for STO operations targeting 55 deg \( \theta \).

The second phase of the testing was to determine the nozzle rotation schedule for the newly defined STO task. The major test criteria was to determine \( V_{ny} \) such that the total distance required to clear 50 ft AGL was minimum and \( a/g \) remained acceptable during climbout providing a repeatable STO task for the average pilot. As a result of the data obtained from the constant airspeed climb tests, initial nozzle angle rotation velocities were chosen from the original nozzle rotation schedule plus 10 KTS. Tests were conducted in a build-up approach by performing lower hover weight ratio tests first. If aircraft flight path acceleration and handling qualities were qualitatively and quantitatively acceptable throughout the STO task, \( V_{ny} \) was decreased in 2-5 KTS increments and the test was repeated. \( V_{ny} \) was reduced until minimum acceptable \( a/g \) was achieved or pilot comments indicated that any further reduction in \( V_{ny} \) would have adverse effects on the flying qualities and repeatability. Trim was initially set using the original trim schedule. During STO testing, trim was varied for each loading tested in order to develop the optimum trim schedule. A removable mechanical throttle stop was used so that engine RPM cutback did not occur due to engine temperature limits, thus guaranteeing that the hover weight ratio would remain reasonably constant throughout the STO.

**Test Results**

Test data showed the nozzle angle crossover point to be at 1.35 \( W/W_h \) (with approximately 10 KCAS performance safety margin) for 55 deg \( \theta \). If a pilot were to perform a 14 deg pitch attitude climbout with 55 deg \( \theta \) above 1.35 \( W/W_h \), he would sense that the aircraft was not accelerating, and in fact the aircraft would begin to stagnate, inhibiting the pilot from transitioning from semijetborne flight to wingborne flight. Constant airspeed climb tests for 50 deg \( \theta \) showed acceptable \( a/g \) for all \( W/W_h \) above the nozzle angle crossover point of 1.35 \( W/W_h \). When the aircraft acceleration data was plotted against the current original \( V_{ny} \) curve, the results showed that the original curve would cause a pilot to be below the minimum acceptable \( a/g \) for a target \( V_{ny} \) at hover weight ratios above 1.30 for STO operations using 55 deg nozzle angle. Therefore, during the originally defined STO task, a pilot would begin to experience stagnation (lack of acceleration). Both fleet and test pilot comments prior to this evaluation supported this finding.

The final \( V_{ny} \) schedule was then plotted in the form of velocity parameter versus hover weight ratio, for corresponding regions of target \( \theta \). A comparison between data for the original STO task and the developed STO task depicting ground distance required to clear 50 AGL at the same test conditions showed the distances to be approximately the same (within \( \pm 200 \) ft, positive for \( W/W_h \) below the nozzle angle crossover point, and negative for \( W/W_h \) above the nozzle angle crossover point). Therefore, new nozzle rotation schedule and trim schedule produced no major change in required distances, increased flight path acceleration, and provided adequate handling qualities allowing the pilot to perform a safe and repeatable STO for all operational hover weight ratios tested.

The lower hover weight ratio data showed that the distance to clear 50 ft AGL using the maximum STO performance was slightly more then the original STO method. This is a result of using the pitch attitude capture technique as opposed to AOA capture. The lower hover weight ratio tests were conducted at
lower gross weights. This provided for lower angles of attack, thus lower rates of climb. However, the ability of the aircraft to accelerate in the axial direction was enhanced. Performance can be further optimized if pitch attitude (as well as $\theta$) is optimized relative to hover weight ratio such that rate of climb is maximized while keeping adequate flight path acceleration. Performance could also be further optimized by just increasing target $\theta$, resulting in a decrease in $a/g$. However, as stated earlier this increases the complexity of the STO task. Since the pitch attitude was chosen for the most likely operational condition, and because performance for lower hover weight ratio conditions was adequate, the constant pitch attitude capture task was considered acceptable for all operational hover weight ratios tested.

**Conclusion**

Using the concepts of thrust vector rotation schedule and minimum acceptable $a/g$ allowed the development of an optimum STO technique with associated $V_{\text{eq}}$ schedule, nozzle angle schedule, and stabilator trim schedule optimizing STO performance and producing a safe, repeatable STO task for all operational hover weight ratios. Advantages to the developed test approach included:

1. Increased flight test efficiency. Minimum flight testing was needed to determine the required thrust vector angle crossover points, thrust vector angle schedule, thrust vector rotation velocity schedule, and the trim schedule optimizing attitude capture for various loadings.

2. Development of a STO task accounting for both the handling qualities and performance constraints of a given test vehicle, therefore optimizing the performance and repeatability of the STO technique.

3. The concept of the velocity parameter and hover weight ratio reduced complexity of data presentation and documentation.

Additional benefits can be gained by applying the concept of minimum acceptable $a/g$ along with the developed takeoff performance and $a/g$ equations in order to analyze and develop an optimum STO technique accompanied with associated performance schedules prior to flight testing. This can be particularly useful in the early design phase of an aircraft and further benefits can be gained when applied in conjunction with simulation.

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**References**


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