

TAKE-OFF PERFORMANCE OF VECTORED-JET-THRUST V/STOL AIRCRAFT

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
A_j	cross sectional area of exhaust jet	m^2	ft^2
C_D	drag coefficient		
C_L	lift coefficient		
D	drag	N	lbf
D_M	momentum drag (ram drag)	N	lbf
d_j	diameter of nozzle exit	m	ft
F_G	gross thrust	N	lbf
$f_1, f_2, \dots$	denote functional relationships of type f [...]		
g	acceleration due to gravity	m/s^2	ft/s^2
H_p	pressure height	m	ft
L	lift	N	lbf
$\dot{m}$	mass flow	kg/s	slug/s
$\dot{m}_j$	mass flow in exhaust jet at nozzle exit	kg/s	slug/s
N	engine rotational speed	rev/s	rev/s
p	ambient pressure	N/m^2	lbf/ft^2
q	kinetic pressure	N/m^2	lbf/ft^2
R	radius of curvature of flight path	m	ft
S	wing reference area	m^2	ft^2
s	distance	m	ft
s_a	distance in airborne segment of take-off	m	ft
s_g	distance in ground-run	m	ft
T	ambient temperature	K	K

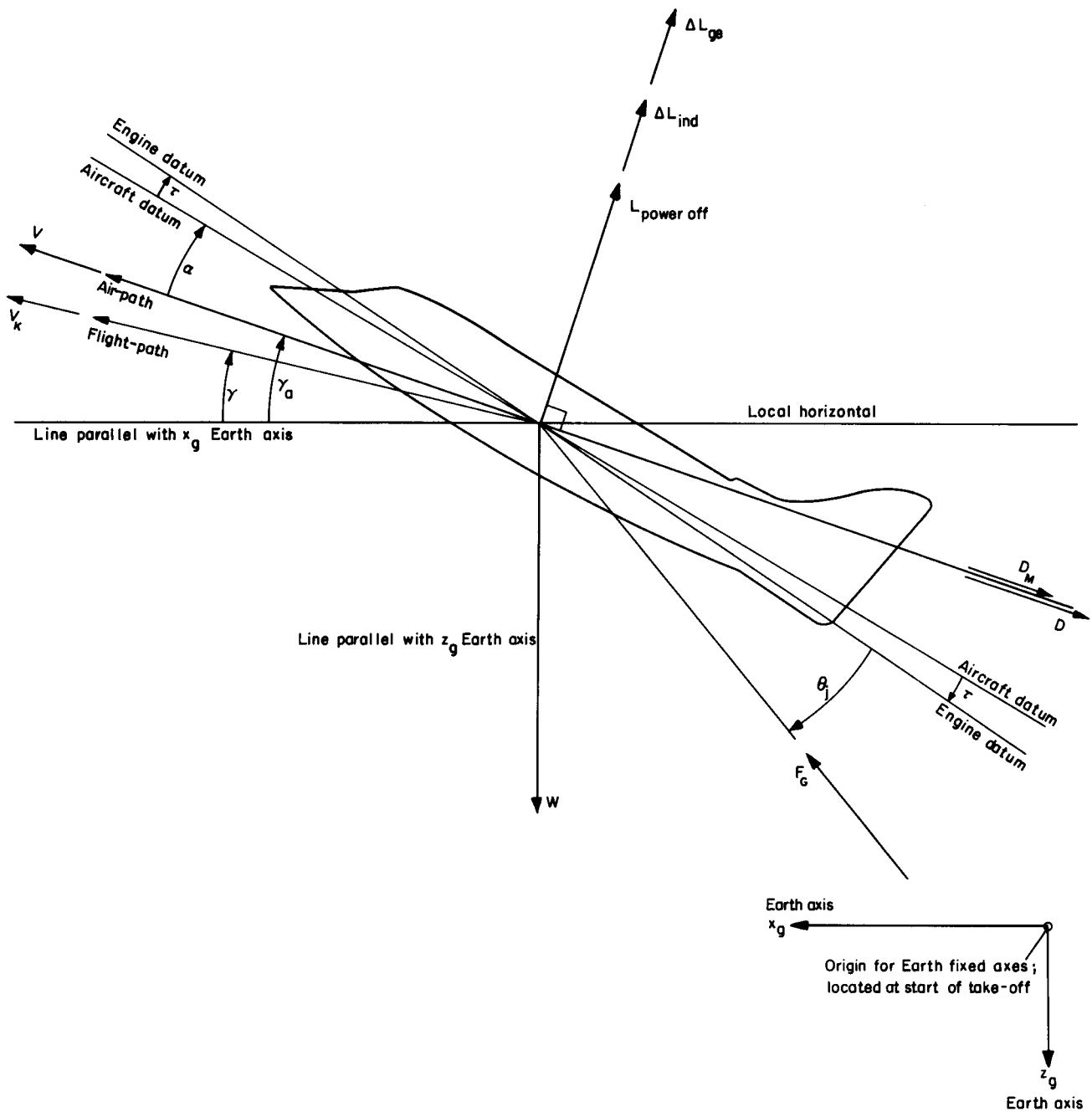
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u_{K_g}	horizontal component of flight-path velocity, V_K , in x_g direction	kn	kn
V	true airspeed (resultant velocity with respect to air)	kn	kn
V_e	equivalent airspeed	kn	kn
V_{e_R}	equivalent airspeed at nozzle rotation	kn	kn
V_{end}	speed relative to deck at end of deck (or ramp)	kn	kn
V_j	jet velocity (true speed) at nozzle exit	kn	kn
V_K	flight-path velocity (resultant velocity with respect to Earth)	kn	kn
V_R	nozzle rotation speed, <i>i.e.</i> true airspeed at nozzle rotation	kn	kn
W	weight	N	lbf
W_H	hover weight (in free air), see Section 5.1	N	lbf
$\bar{W}_H$	mean airborne hover weight, see Sections 7.4.1 and 8.5	N	lbf
$W_{H_{datum}}$	mean hover weight at datum setting in ISA sea level conditions (see Section 8.4)	N	lbf
W_{H_g}	hover weight corresponding to powerplant setting during ground-run	N	lbf
w_g	component of true airspeed, V , in z_g direction	kn	kn
w_{K_g}	component of flight-path velocity, V_K , in z_g direction	kn	kn
x_g	normal Earth-axis co-ordinate (Earth fixed), see Sketch 1.1	m	ft
x_{jet}	distance downstream of jet nozzle exit	m	ft
z_g	normal Earth-axis co-ordinate (Earth fixed), see Sketch 1.1	m	ft
α	angle of attack; angle between aircraft datum and projection of V on to aircraft plane of symmetry	deg	deg
γ	angle of climb (flight-path inclination angle), $\sin \gamma = -w_{K_g}/V_K$	deg	deg
γ_a	air-path angle of climb (air-path inclination angle), $\sin \gamma_a = -w_g/V$	deg	deg
$\Delta C_{L_{ge}}$	change in C_L due to ground effect		
ΔF_{ind}	jet-induced force on intake	N	lbf

ΔL_{ge}	change in lift due to ground effect	N	lbf
ΔL_{ind}	jet-induced change in lift ("lift loss" = $-\Delta L_{ind}$)	N	lbf
Δn	change in normal load factor from steady level flight value		
ΔV_{ind}	jet-induced change in V	kn	kn
δ	relative pressure, p/p_0		
$\Delta \alpha_{ind}$	jet-induced change in α	deg	deg
θ	relative temperature, T/T_0		
Θ_j	jet nozzle angle relative to engine datum	deg	deg
Θ_r	runway or ramp angle, positive uphill	deg	deg
$\Theta_{r\ nom}$	nominal ramp angle, see Section 8.4.2	deg	deg
ρ	density of air	kg/m ³	slug/ft ³
ρ_j	density of exhaust jet gas at nozzle exit	kg/m ³	slug/ft ³
σ	relative density, ρ/ρ_0		
σ	standard deviation in launch speed (Section 8.2.2 only)	kn	kn
σ_j	relative density, ρ_j/ρ_0		
τ	angle between engine datum and aircraft datum	deg	deg
μ_R	rolling resistance coefficient		

Subscripts

<i>bal</i>	denotes value in balanced, <i>i.e.</i> steady level, partially jetborne flight (zero acceleration)
<i>eff</i>	denotes effective value
<i>launch</i>	denotes airspeed at end of deck or ramp
<i>opt</i>	denotes optimum value
<i>power-off</i>	denotes value with power off
<i>screen</i>	denotes value at take-off screen
<i>s</i>	denotes value at static conditions
<i>ss</i>	denotes sea strike
<i>0</i>	denotes value at sea level in International Standard Atmosphere, ISA



Sketch 1.1 Guide to axes, angles and forces (unbanked flight) (arrows show positive directions)

2. INTRODUCTION

This Data Item presents some of the more important aspects of take-off performance specific to vectored-jet-thrust aircraft (see References 5, 7, 12, 13) including some general approaches to the estimation and presentation of performance in the short take-off (STO) and “ski-jump” (curved-ramp) modes. In principle, the calculation of vectored-jet-thrust aircraft take-off performance is similar to that for conventional take-off (CTO) aircraft. The differences occur mainly in the airborne segment. Consequently, the Item concentrates on methods of calculating airborne distances and of optimising the overall distance from rest to the take-off screen. Where procedures are similar to those used for conventional take-off calculations, the user is directed to Reference 15 which contains a very detailed treatment of the step-by-step calculation of take-off performance.

Section 3 considers the implications of the vectored-jet-thrust aircraft configuration for short take-off performance, airframe aerodynamics and powerplant performance.

Section 4 presents the basis of a unique approach to take-off performance calculations based on the possibility of measuring steady “point” performance at airspeeds down to zero with a vectored-jet-thrust aircraft.

Section 5 introduces the use of non-dimensional* parameters for take-off performance work with vectored-jet-thrust aircraft. With this type of aircraft it is possible to obtain a simple direct measure of installed thrust (the aircraft weight) in the hover, and a consequence of this is that non-dimensional methods* may be used for the analysis and presentation of take-off performance. The application of these methods to take-off performance calculations is considered further in Sections 7.2 to 7.4 and 8.4.

Section 6 deals with the step-by-step calculation of the airborne segment of a short take-off. The calculation methods include the application of the point-performance data discussed in Section 4.

Section 7 discusses the procedures whereby the short take-off distance from rest to the take-off screen may be optimised for land-based operations.

Section 8 considers the special features of take-off with a curved ramp (ski-jump), specifically with reference to ship-based operations.

Appendix A presents a review of those jet-induced aerodynamic effects that are of significance for this Data Item.

Appendix B provides the background to the choice of non-dimensional* parameters used in Sections 5, 7.2 to 7.4 and 8.4.

* Truly non-dimensional relationships (see, for example, Reference 3, Appendix A, Equation (A7)) are rarely used since more convenient, modified, forms can be derived if:

- (i) any quantities which are constant for a particular aircraft type are omitted, for example areas, linear dimensions,
- (ii) atmospheric properties are expressed as ratios to sea level standard values,
- (iii) engine rotational speed and hence engine power are each expressed as fractions or percentages of reference values.

In consequence of (i) and (ii) above, the parameters in this Item are not non-dimensional; however, it is usual to refer to them as “non-dimensional” and the practice is retained here. In addition, the rules of dimensional analysis permit the non-dimensional parameters to be regrouped by multiplication or division, provided the number of such parameters is unchanged (see, for example, Reference 3, Appendix A, Equations (A8) and (A9)).

3. IMPLICATIONS OF THE VECTORED-JET-THRUST AIRCRAFT CONFIGURATION

This Section discusses briefly those special features associated with the vectored-jet-thrust configuration (some of these are highly-accentuated versions of effects present in other types of aircraft). Sections 3.1, 3.2 and 3.3 consider performance, aerodynamic and powerplant aspects respectively by making comparisons with conventional aircraft practice, *i.e.* a knowledge of the latter is presumed. For a wider background discussion of the characteristics and merits of the vectored-jet-thrust aircraft configuration, see References 5, 7, 12, 13).

3.1 Short Take-Off Performance

For a vectored-jet-thrust aircraft operating in the short-take-off (deflected nozzles) mode, the take-off performance and associated speeds are not related directly to wingborne stalling speeds. For this class of aircraft (as for conventional types) all the installed thrust may be used for acceleration in the ground run so that the controlling parameters for a short take-off are the speed at which thrust vectoring is applied and the associated nozzle angle used. In practice, however, forward-flight angle of attack limitations in the airborne segment of the take-off will probably be imposed.

For hovering flight with vectored-jet-thrust aircraft, the gross thrust required is a function only of the aircraft weight and the induced aerodynamic forces, which are in turn proportional to the gross thrust, see Appendix A. The consequent ability to obtain a simple direct measure of installed thrust in the hover (*i.e.* the aircraft weight) makes possible the use of non-dimensional methods for the analysis and presentation of take-off performance more easily than is the case for conventional take-off performance. See Sections 5, 7.2 to 7.4 and 8.4 for applications of these methods and Appendix B regarding the choice of non-dimensional parameters.

3.2 Aerodynamics

Jet-induced external aerodynamic effects on lift and pitching moment are significant whether the aircraft is in or out of ground effect.

While the **power-off** low-speed aerodynamics of a jet V/STOL aircraft are essentially the same as those of a conventional aeroplane, and may be represented by data in a format similar to that Table 7.2 of Reference 15, significant modifications are produced by the interactions between the jets and the external airflow and/or the ground. It is not possible to deal fully here with these aerodynamic effects due to their complexity and, in practice, this complexity also dictates that the necessary data are obtained from model and flight tests. Appendix A presents a review of those jet-induced aerodynamic effects that are of significance here and, in particular, the Appendix demonstrates the fundamental importance of effective jet velocity ratio, $(V_j/V)_{eff}$, in determining the magnitude of the induced lift loss – expressed by the ratio $(\Delta L_{ind}/F_G)$.

Note that the effective jet velocity ratio, $(V_j/V)_{eff}$, alone may not be sufficient to describe the interaction of powerplant(s) and airframe for all flight conditions. In some cases the distribution of the parameter between nozzles may have to be taken into account.

3.3 Powerplant

3.3.1 Thrust concepts

For all high-performance jet aircraft it is usual to consider the gross thrust, F_G , and momentum drag, D_M , separately – see Reference 1 for definitions. For vectored-jet-thrust aircraft **this is essential**. In this Data Item, whenever the term “thrust” is used, gross thrust is implied, for example as in “deflected thrust”.

3.3.2 Lift ratings

The need for maximum possible thrust for take-off, combined with the shorter times involved compared with those for conventional take-offs, leads to the introduction of additional “Lift-Ratings” which may be available for periods as short as 5 seconds.

3.3.3 Jet pipe temperature limiter

Since the pilot is fully occupied during take-off, engine temperature must be monitored and power setting limited automatically. Typically, the exhaust gas temperature is sensed by probes that are similar in essentials to those considered in Section 3.4.2 and Appendix B of Reference 6 – specifically they are likely to have lag characteristics of the dual-time-constant type.

The thrust available while the engine is subject to control by a jet pipe* temperature limiter (JPTL) is transient and depends on the response characteristics of both the engine and the JPTL. Realistic simulation of engine thrust for take-off calculations therefore requires the modelling of these characteristics.

3.3.4 Reaction control effects

The need for adequate flight control forces at speeds down to zero is unique to V/STOL aircraft and on jet aircraft is met by the use of reaction controls consisting of small jet nozzles at the aircraft's extremities. The thrusts from these nozzles are varied by inputs to the same overall control system as operates the aerodynamic flying controls. The use of reaction controls creates an additional demand for bleed air from the engine which has the direct effect of reducing its thrust. However, because of the rise in exhaust gas temperature associated with the reduced mass flow, there is a secondary effect on thrust if the jet pipe temperature limit is reached, see Section 3.3.3. On the other hand, there may be some compensating and useful thrust from the pitch and roll reaction controls themselves. The demands for bleed air are an interface between performance and stability and control.

3.3.5 Intake effects

The conventional representation of intake effects on engine performance is in terms of an average total pressure loss between free stream and engine entry. However, for modern installations, and particularly those where the location of the powerplant may require the use of short S-shaped intake ducts, the effects of flow distortion (not necessarily corresponding to any **flow** “losses”) can result in **engine performance** losses beyond those that can be ascribed to average total pressure loss. Flow distortion, of course, has implications for engine handling as well.

For aircraft where there is a substantial jet-induced flow field, the intake is also subject to a force induced by that flow, with implications for both force and moment balances on the aircraft, particularly in the hover. This topic is considered in Section A5 of Appendix A.

* Or otherwise located.

4. STEADY LEVEL PARTIALLY JETBORNE (PJB) FLIGHT

Steady level partially jetborne (PJB) flight is achieved when the aircraft maintains constant speed and altitude in conditions that require the jets to be deflected to obtain sufficient overall lift (jet plus aerodynamic) to balance the weight.

4.1 Use of Calculated and Measured PJB Data in Take-Off Performance Calculations

The step-by-step calculation of performance described in Section 6 requires, as input, accurate values of the forces (or their resultant) acting on the aircraft throughout the airborne segment of the take-off. Systematic aerodynamic data are usually obtained from model tests or by estimation, while powerplant data are provided by the manufacturer. However, some (at least) of the data must be determined from flight test – if only to validate the predictions. Flight-test methods such as those of Sections 5 and 6 of Reference 4 might be used to determine aircraft accelerations and, subsequently, to deduce component forces on the aircraft (Reference 14 reports an exploratory investigation of these techniques applied to a vectored-jet-thrust aircraft). However, an alternative approach is to take advantage of the ability of a vectored-jet-thrust aircraft to maintain steady level partially jetborne flight (in which the resultant force on the aircraft is zero) at all airspeeds down to zero.

Figure 1 shows an example of the relationship between PJB level speed, angle of attack, engine speed and nozzle angle for fixed airframe configuration, weight and ambient conditions. Such charts may be constructed initially using wind-tunnel and engine test-bed data and can provide guidance during flight development work towards transition from/to hover to/from wingborne flight. The basis of this type of presentation is discussed in Section 4.2 and Appendix B.

Flight determination of all or parts of Figure 1 provides confirmation of predicted aerodynamic characteristics. In addition, since the airborne segment of the take-off employs small accelerations along and normal to the flight path, it may be regarded as a sequence of perturbations from PJB flight conditions. Data of the type shown in Figure 1 may then be used, when non-dimensionalised (see Section 5), in such take-off calculations, see Section 6.

4.2 Balance of Forces in Steady Level PJB Flight

From Sketch 1.1 the balance of forces along and normal to the air path for steady level PJB flight may be written as

$$F_G \cos(\Theta_j + \alpha + \tau) - D - D_M = 0 \quad (4.1)$$

$$F_G \sin(\Theta_j + \alpha + \tau) + L_{power\ off} + \Delta L_{ind} - W = 0. \quad (4.2)$$

In Equations (4.1) and (4.2) it is assumed that PJB flight is in free air (no ground effect) and that jet-induced effects on drag, D , are negligible. The functional forms of the forces in Equations (4.1) and (4.2) are as follows.

$$F_G = f_1[N, V_e, H_p, T],$$

$$D_M = f_2[N, V_e, H_p, T],$$

$$L_{power\ off} = f_3[V_e, \alpha],$$

$$D = f_4[V_e, \alpha],$$

$$\left. \begin{aligned} \Delta L_{ind} &= f_5[(V_j/V)_{eff}, F_G, \Theta_j] \\ &= f_6[V_e, F_G, \Theta_j] \end{aligned} \right\} \text{ see Appendix A, Section A2.}$$

Thus, with the inclusion of aircraft weight, the relationships of Equations (4.1) and (4.2) may be expressed in terms of the seven variables,

$$H_p, N, T, V_e, W, \alpha, \Theta_j.$$

For a fixed combination of weight, altitude and temperature, the number of variables is reduced to four (N, V_e, α, Θ_j). The functional relationships are such that, within the practical operating ranges of the variables, a vector function can be defined between any pair of these variables and the remaining pair, *i.e.* if arbitrary values are assigned to two of the variables, the other two are determined, see Figure 1.

5. NON-DIMENSIONAL* PARAMETERS FOR V/STOL FLIGHT

A non-dimensional treatment can be applied to vectored-jet-thrust aircraft take-off performance with advantages in the simplification of flight-test planning, in the correlation and presentation of results and in the ease of derivation of performance for specified conditions. This Section develops the basic ideas and applies them to steady level PJB flight characteristics.

5.1 Take-Off Weight Ratio

The concept of take-off weight ratio, W/W_H , originates in flight-test work related to vertical take-off, but is useful in the wider context of short take-offs.

Free-air hover for a given aircraft configuration and weight, altitude and temperature requires a particular engine setting, and a corresponding value of installed gross thrust, while airframe and intake force components arising from the jet-induced flow are shown in Sections A1 and A5 of Appendix A to be proportional to that thrust. In consequence, the still-air hover weight, W_H , is directly proportional to the installed static gross thrust, F_{G_s} .

For vertical take-off (VTO) extra thrust is required (for a given weight) compared to that needed to hover in free air. This arises from the extra “lift-loss[†]” in adverse ground effect (for some V/STOL aircraft the ground effect in VTO may be favourable but the general argument is still applicable) and from the requirement for a comfortable rate of ascent to (free-air) hover height (there is considerable damping of vertical motion due both to the incremental lift-loss and to momentum drag). Hence the ratio of VTO weight, W , to the hover weight, W_H , which could just be sustained at the maximum engine speed available for VTO, is less than unity; W/W_H is referred to as the take-off weight ratio. When applied to flight-test results, the ratio W/W_H is useful in removing the variability in absolute take-off weight due to varying atmospheric conditions. Flight tests can also be used to establish the practical maximum value of W/W_H as a function of wind speed and nozzle deflection.

For short take-off (STO) the aim is to lift more weight than in vertical take-off and $W/W_H \geq 1$. The greater the value of W/W_H , the greater the take-off speed and distance, *i.e.* W/W_H provides, for short take-offs, a measure of the relative proportions of lift generated by powerplant and wing.

* Truly non-dimensional relationships (see, for example, Reference 3, Appendix A, Equation (A7)) are rarely used since more convenient, modified, forms can be derived if:

- (i) any quantities which are constant for a particular aircraft type are omitted, for example areas, linear dimensions,
- (ii) atmospheric properties are expressed as ratios to sea level standard values,
- (iii) engine rotational speed and hence engine power are each expressed as fractions or percentages of reference values.

In consequence of (i) and (ii) above, the parameters in this Item are not non-dimensional; however, it is usual to refer to them as “non-dimensional” and the practice is retained here. In addition, the rules of dimensional analysis permit the non-dimensional parameters to be regrouped by multiplication or division, provided the number of such parameters is unchanged (see, for example, Reference 3, Appendix A, Equations (A8) and (A9)).

† See Appendix A, Section A1.

Since short take-offs are carried out at engine ratings that may be considerably higher than those available for hover (the relatively long duration of the latter prevents the use of short-period “lift ratings”, see Section 3.3.2), some extrapolation of measured hover-weight data may be required. This requires a knowledge of the variation of intake installation loss at the higher power settings, but is simplified by the proportionality of lift-loss to installed gross thrust, see Appendix A, Section A2.

5.2 “Non-Dimensional” Partially Jetborne Flight Characteristics

The dimensional PJB characteristics shown in Figure 1 apply to a particular combination of W , H_p , and T while the objective of non-dimensionalisation is to produce unique presentations applicable to all weights and atmospheric conditions. Assuming that for a given airframe configuration the steady level PJB flight conditions may be fully represented by the seven variables quoted in Section 4.2, the non-dimensional relationships can be expressed as

$$\frac{V_e}{W^{1/2}} = f_7 \left[\frac{W}{W_H}, \alpha \right]$$

$$\Theta_j = f_8 \left[\frac{V_e}{W^{1/2}}, \alpha \right].$$

Examples of this presentation are given in Figures 2 and 3. See Appendix B for the derivation and validation of these parameters.

6. STEP-BY-STEP CALCULATION OF SHORT TAKE-OFF AIRBORNE* TRAJECTORY

This Section describes the method of calculating short take-off performance for both land- and ship-based operations using step-by-step calculation methods, with particular emphasis on the use of PJB data in defining the forces acting on the aircraft.

6.1 Equations of Motion

In principle, the airborne path can be calculated by the step-by-step integration of the full equations of motion, which, in local Earth axes (see Sketches 1.1 and 6.1) are,

$$\frac{W}{g} \ddot{x}_g = F_G \cos(\Theta_j + \tau + \alpha + \gamma_a) - \sin \gamma_a (L_{power-off} + \Delta L_{ind} + \Delta L_{ge}) - (D_M \cos \gamma_a - D \cos \gamma_a) \quad (6.1)$$

$$-\frac{W}{g} \ddot{z}_g = F_G \sin(\Theta_j + \tau + \alpha + \gamma_a) + \cos \gamma_a (L_{power-off} + \Delta L_{ind} + \Delta L_{ge}) - (D_M \sin \gamma_a - D \sin \gamma_a - W). \quad (6.2)$$

Hence from the initial aircraft position and velocity, appropriate step-by-step numerical integration procedures provide the take-off trajectory and aircraft velocity-time history. The general calculation method is applicable to all forms of short take-off and details of the practical calculation procedures are given in Section 6.3 for both land- and ship-based operations. The use of the calculation method for optimising take-off performance is discussed in Sections 7 and 8.

6.2 Equations of Motion for Use with PJB Data

During take-off the accelerations along and normal to the flight path are small and one method of solving Equations (6.1) and (6.2) is to utilise the data for partially jetborne flight discussed in Section 4. To do this, Equations (6.1) and (6.2) must be rewritten, as follows, in terms of a perturbation from the steady level PJB flight condition illustrated on the left-hand-side of Sketch 6.1, to a climbing accelerating flight condition as on the right-hand-side of Sketch 6.1.

For any point in the airborne segment (or “step” in its calculation) the values of the parameters hover weight, W_H , equivalent airspeed, V_e , and angle of attack, α , taken together, can be used to define a corresponding steady level partially jetborne flight condition (see Figures 2 and 3). The corresponding gross thrust may also be determined. For such a PJB flight condition, if the aircraft weight and nozzle angle are denoted W_{bal} and $\Theta_{j\ bal}$ (signifying balanced-flight, see left-hand-side of Sketch 6.1), the sum of the airframe and momentum drags is given by Equation (4.1) as

$$(D + D_M) = F_G \cos(\Theta_{j\ bal} + \alpha + \tau). \quad (6.3)$$

Similarly, the power-off lift is given by Equation (4.2) as

$$L_{power\ off} = W_{bal} - \Delta L_{ind, bal} - F_G \sin(\Theta_{j\ bal} + \alpha + \tau) \quad (6.4)$$

where $\Delta L_{ind, bal}$ is the value of ΔL_{ind} associated with the PJB flight condition.

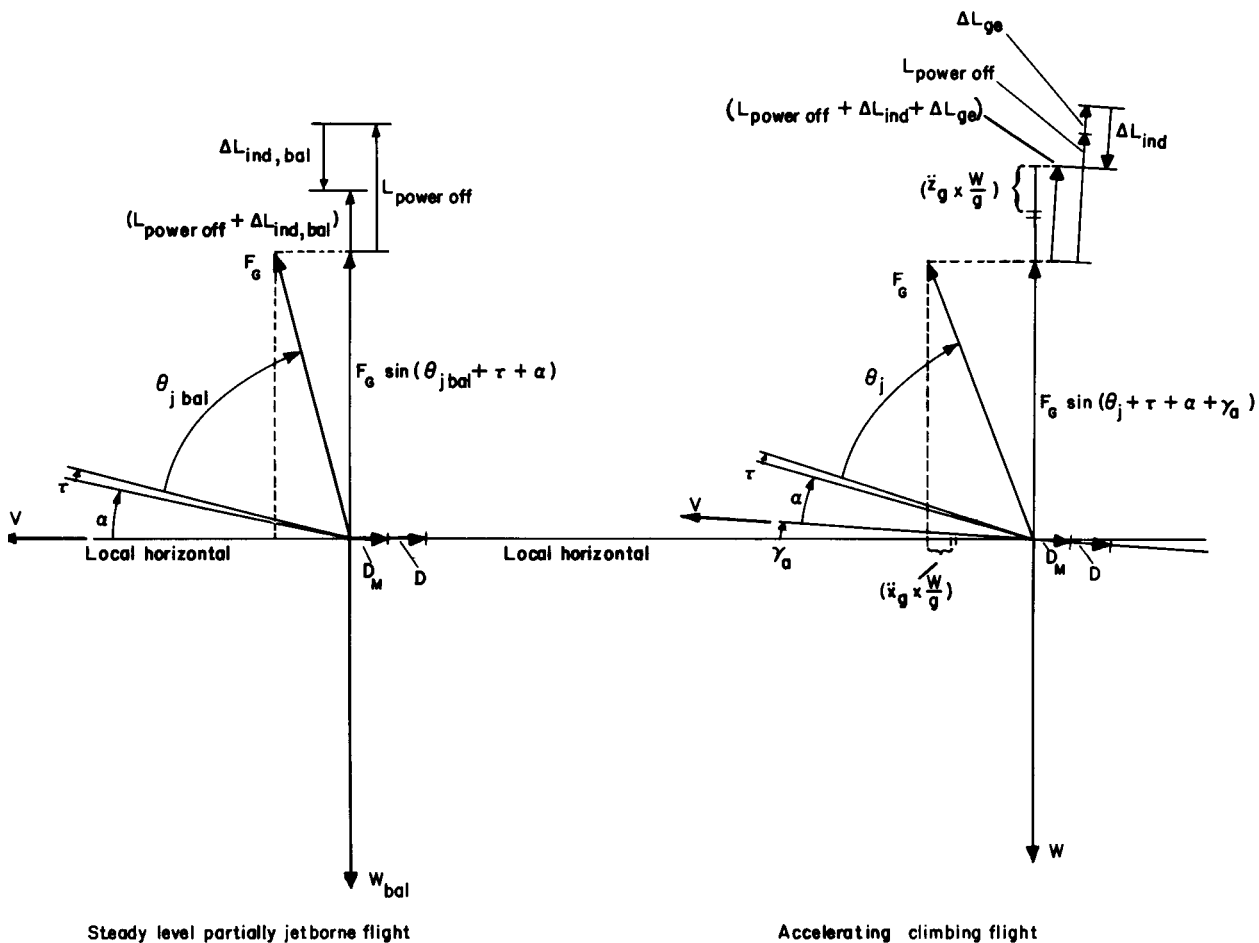
* “Airborne” is used to denote this segment of the take-off and not to imply that the aircraft is wholly supported by wing-generated lift.

Since the values of $(D + D_M)$ and $L_{power\ off}$ are the same for both the PJB and actual (accelerating) flight conditions (*i.e.* on both left-hand and right-hand-sides of Sketch 6.1), these parameters may be eliminated from Equations (6.1) and (6.2) by substituting from Equations (6.3) and (6.4). The resulting expressions for accelerations along and normal to local Earth axes are as follows.

$$\frac{W}{g} \ddot{x}_g = F_G [\cos(\Theta_j + \tau + \alpha + \gamma_a) - \cos(\Theta_{j\ bal} + \tau + \alpha + \gamma_a)] - W_{bal} \sin \gamma_a - [\Delta L_{ind} - \Delta L_{ind, bal} + \Delta L_{ge}] \sin \gamma_a \quad (6.5)$$

$$-\frac{W}{g} \ddot{z}_g = F_G [\sin(\Theta_j + \tau + \alpha + \gamma_a) - \sin(\Theta_{j\ bal} + \tau + \alpha + \gamma_a)] - [W - W_{bal} \cos \gamma_a] + [\Delta L_{ind} - \Delta L_{ind, bal} + \Delta L_{ge}] \cos \gamma_a. \quad (6.6)$$

Thus the accelerating forces are equal to the actual forces minus the corresponding PJB forces (note that for take-off from a ship the term ΔL_{ge} can usually be ignored for the airborne segment).



Sketch 6.1 Vector diagrams of PJB and accelerating flight conditions

6.3 Calculation Procedures

Sketch 6.2 gives a summary of the calculation procedure for the airborne segment. To calculate a particular airborne trajectory, values are required for aircraft weight, engine speed (either constant or as a function of time), nozzle angle, nozzle rotation or launch* speed, runway or ramp gradient(s), wind speed, pressure height and ambient temperature. The calculations are simplified if angle of attack is specified as a function of time (although there is no reason why they should not include the “pilot in the loop”, in which case the angle of attack is calculated simultaneously with the trajectory according to some prescribed pilot control actions). The take-off technique is to rotate the nozzles to a pre-determined angle at the nozzle rotation or deck-end* speed and one of the objectives of the calculations is to establish optimum “scheduled” values of both nozzle angle and nozzle rotation or launch* speed, see Sections 7 and 8.

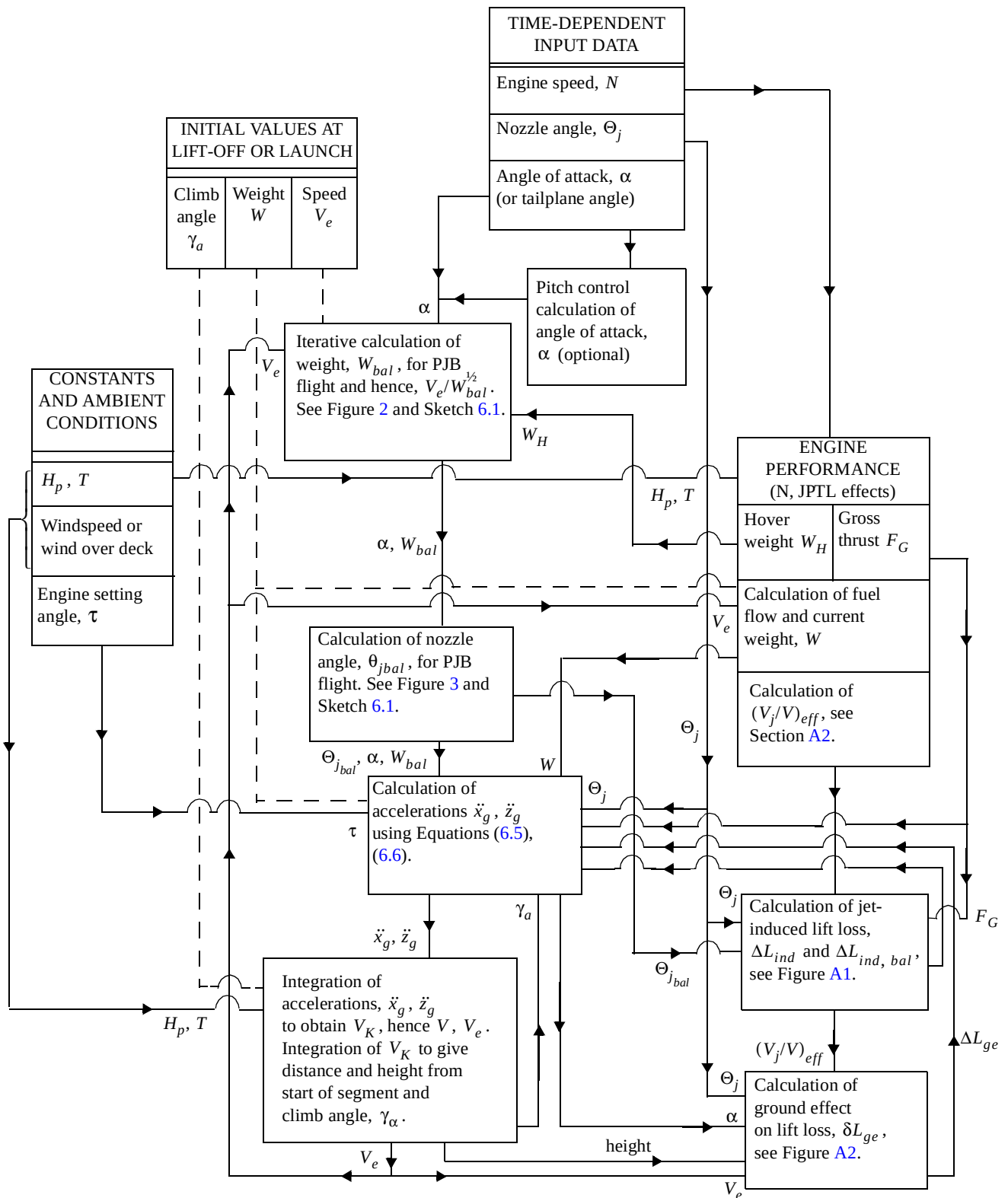
Knowledge of the engine setting (speed) for take-off, including, in general, the transient response under JPTL control, enables the value of hover weight, W_H , to be determined for each step in the calculation. For known values of W_H , V_e and α the non-dimensional PJB data (see Figures 2 and 3) may be used to determine the weight of aircraft, W_{bal} , that could be sustained in steady, level, PJB flight at these conditions (by an iterative procedure) and the corresponding nozzle angle, Θ_{jbal} . During the take-off the actual lift-loss differs slightly from that in PJB flight due to the different nozzle angle. Given the value of W_H already calculated it follows, from the discussions of Section 5.1 and Appendix B, that knowledge of F_{G_s}/W_H , together with a small allowance for the effect of forward speed, enables the installed gross thrust, F_G , and effective jet velocity ratio to be determined. From these data and a knowledge of the lift-loss characteristics in the form of Figure A1 the perturbation of lift-loss, i.e. the quantity $[\Delta L_{ind} - \Delta L_{ind, bal}]$ in Equations (6.5) and (6.6), can be established.

For the airborne segment of ship-based take-offs, the term ΔL_{ge} can be omitted from Equations (6.5) and (6.6). For land-based short take-off the presence of ground effect must be taken into account. From wind-tunnel data such as those presented in Figure A2 it is straightforward to include the appropriate force in the step-by-step calculation procedure. Its dependence on angle of attack, nozzle angle, effective jet velocity ratio and height, however, requires the preparation of a significant quantity of data in addition to those required for ship-based take-offs. Note that although ground effect falls off fairly rapidly with height this does not diminish its importance. For example, Figure A2 suggests that the ground effect is of greatest significance for only about 25 per cent of the height from nozzle rotation to the (50 ft) screen but for a typical V/STOL aircraft this can represent up to 50 per cent of the time taken to that screen.

6.4 Practical Flight Considerations

The short take-off of a vectored-jet-thrust aircraft from a ship is generally likely to be simpler to execute, from the pilot's point of view, than a land-based STO due to the absence of ground effect. As indicated in Appendix A, the jet-induced effects in forward flight in free-air include a (generally nose-up) pitching moment. The ground effect in STO, on nozzle deflection, is usually the reverse; the “fountains” produced by reflection of the interacting jet flows after impingement on the ground re-impinge on the rear fuselage and/or tailplane and produce a nose-down moment. This adverse (with respect to rotation) initial moment followed by the change to adverse (with respect to “capture” of the target angle of attack) nose-up moment as ground effect disappears, together with the unstable nature of the latter, tend to make the land-based STO the more demanding task. In contrast, a ship-based take-off may, initially, be made “hands-off”.

* “Launch speed” is the **airspeed** (true, equivalent or indicated, as appropriate) at the end of the deck or ramp. “Deck-end speed” is the **speed relative to the deck** at the end of the deck or ramp.



Sketch 6.2 Calculation procedure for airborne segment