

ENERGY METHOD FOR ANALYSIS OF MEASURED AIRSPEED CHANGE IN LANDING AIRBORNE MANOEUVRE

1. NOTATION AND UNITS

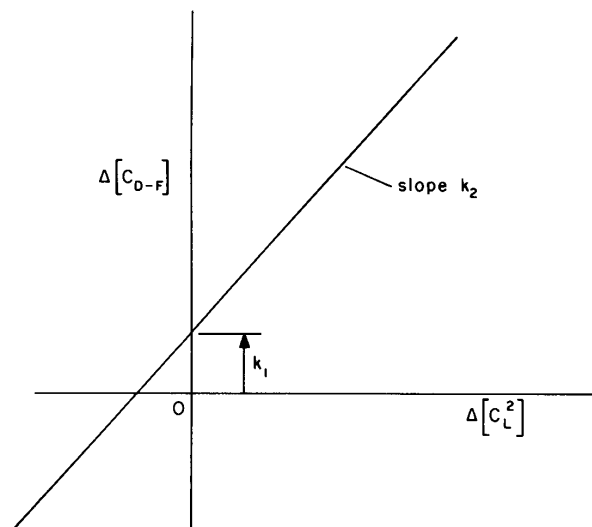
		<i>SI</i>	<i>British</i>
A	aspect ratio, b^2/S		
b	wing span	m	ft
C_{D-F}	coefficient of drag-minus-thrust, $(D-F)/qS$		
C_L	lift coefficient, L/qS (usually taken as W/qS when calculating $C_{L_{screen}}$ and $C_{L_{TD}}$, but see Section 3.1)		
D	airframe drag	N	lbf
F	thrust component along flight path, per aircraft	N	lbf
F_L	thrust component in lift direction	N	lbf
g	acceleration due to gravity	m/s ²	ft/s ²
H	height	m	ft
h_{screen}	screen height, height between initial and final points in airborne manoeuvre in landing	m	ft
h_w	wing height above ground ("static" value, taken at aerodynamic mean chord of gross wing with aircraft stationary)	m	ft
k_1, k_2	parameters defined in Equation (4.1) and Sketch 1.1		
L	lift	N	lbf
m	aircraft mass	kg	slug
n	normal load factor, $(L + F_L)/W$		
q	kinetic pressure, $\rho V^2/2 (= \rho_0 V_e^2/2)$	N/m ²	lbf/ft ²
S	wing reference area	m ²	ft ²
s	horizontal distance travelled	m	ft
s_a	horizontal distance travelled from screen to touchdown, in still air	m	ft
t	time	s	s
t_a	time taken from screen to touchdown	s	s
V	true airspeed	m/s	ft/s
V_e	equivalent airspeed	m/s	ft/s

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V_g	groundspeed horizontal component	m/s	ft/s
V_w	headwind component	m/s	ft/s
$V_{w_{av}}$	average headwind component along runway, taken as value between $(h_{screen} + h_w)$ and h_w	m/s	ft/s
W	aircraft weight, mg	N	lbf
γ	inclination of flight path to horizontal, positive for climb ($\tan \gamma = (dH/dt)/V_g$)	deg	deg
$\Delta[C_L^2]$	change in value of C_L^2 between screen and touchdown, $= [C_{L_{TD}}^2 - C_{L_{screen}}^2]$		
$\Delta[C_{D-F}]$	change in value of $[C_{D-F}]$ defined by Equations (3.3) to (3.5)		
Δs_a	reduction in airborne distance due to headwind component along runway	m	ft
ρ	density of air	kg/m ²	slug/ft ²

Subscripts

a	denotes value relative to air and applicable to whole of airborne manoeuvre
$available$	denotes “available” value of $[(D-F)/W]_a$
$required$	denotes “required” value of $[(D-F)/W]_a$
$screen$	denotes value at screen, i.e. initial point in airborne manoeuvre
TD	denotes value at (mainwheels) touchdown
$V_w = 0$	denotes still-air conditions
0	denotes value at sea level in International Standard Atmosphere, ISA



Sketch 1.1 Illustration of relationship used to define k_1, k_2

2. INTRODUCTION

A method is given for the analysis of measurements of change in airspeed in the landing airborne manoeuvre. The method is applicable to fixed-wing aircraft and, in effect, represents the airborne manoeuvre as changes in the lift and drag-minus-thrust coefficients between screen and touchdown. It is applied directly to the measured data and does not involve the incremental adjustment (“reduction”) of results to standard conditions. The inverse (“data expansion”) procedure is also addressed.

The method is based on energy considerations and can be applied to any set of flight-test measurements but is most effective where the landings concerned have a common style*. One such set of landings is that obtained for civil certification to the requirements of References 1, 2, 3, 5, 6, 7. Another would be landings corresponding to the requirements of Reference 4 (now discontinued for new aircraft). A third category would be landings representative of operational practice.

The analysis method is presented in **Section 3** and has been validated using flight-test data for all of the categories mentioned and for a wide range of aircraft types. **Section 4** describes the practical implications of using the analysis method. **Section 5** presents the inverse (“data expansion”) procedure and includes material which reflects experience gained in its use. **Section 6** summarises the methods available for calculating airborne time (which is required as an input to the present method). **Section 7** brings together the various elements, including wind effects, from which airborne distance is calculated. **Section 10** gives an example of the use of the analysis method, with a set of civil-transport certification test measurements, and of the inverse calculation procedure.

Appendix A gives examples of the application of the analysis method to particular sets of test data. These include jet-, fan- and propeller-driven civil and military aircraft and, in one instance, an unpowered aircraft. Among these examples some contain large ranges of values of approach angle, speed, power-cut heights and of landing styles.

* Many of the factors affecting the airborne manoeuvre in landing, including the different styles of manoeuvre, are discussed in Data Item No. 91032 (Reference 11). Reference 11 is referred to whenever appropriate so as to avoid repetition.

3. METHOD OF REPRESENTING FLIGHT-TEST MEASUREMENTS

Measured values of steady approach angle and airspeed, touchdown airspeed and time (or distance) taken in the landing airborne manoeuvre can be used to deduce values of the parameters $\Delta[C_L^2]$ and $\Delta[C_{D-F}]$ and to define, for a set of landings of a particular style, a relationship of the form,

$$\Delta[C_{D-F}] = f(\Delta[C_L^2]). \quad (3.1)$$

In Equation (3.1) $\Delta[C_L^2]$ and $\Delta[C_{D-F}]$ are changes in [lift coefficient]² and in drag-minus-thrust coefficient during the manoeuvre and are defined as follows.

$$\Delta[C_L^2] = C_{L_{TD}}^2 - C_{L_{screen}}^2, \quad * (3.2)$$

$$\Delta[C_{D-F}] = [C_{D-F}]_a - [C_{D-F}]_{screen}, \quad * (3.3)$$

$$= \left[\frac{D-F}{qS} \right]_a - \left[\frac{D-F}{qS} \right]_{screen}, \quad * (3.4)$$

$$\approx C_{L_{TD}} \left[\frac{D-F}{W} \right]_a - C_{L_{screen}} \tan(-\gamma_{screen}). \quad **\dagger (3.5)$$

The $\approx$ sign is used since $C_{L_{TD}}$ is the value at touchdown while $[(D-F)/W]_a$ is a value applicable to the entire manoeuvre (see Section 8). Values of $C_{L_{screen}}$, $C_{L_{TD}}$ and of $[(D-F)/W]_a$ are derived as indicated in Sections 3.1 and 3.2 respectively.

3.1 Derivation of Lift Coefficients $C_{L_{screen}}$ and $C_{L_{TD}}$

For most purposes connected with this Data Item, values of $C_{L_{screen}}$ and $C_{L_{TD}}$ can be calculated using

$$C_L = \frac{W}{qS}. \quad (3.6)$$

A more general expression for C_L , which has only limited application here, is

$$C_L = \frac{nW - F_L}{qS}. \quad (3.7)$$

The thrust component, F_L , in the lift direction is negligible for most aircraft on approach but should be taken into account if, for example, the method is applied to vectored-jet-thrust aircraft.

The normal load factor, n , for most *steady* approaches may be taken as unity with negligible error – less than 1 per cent for approach angles up to -8° . For very steep approaches, such as those associated with unpowered low L/D aircraft, proper account should be taken of forces acting, *i.e.* $L = [W \cos(-\gamma) - F_L]$; $n = \cos(-\gamma)$.

The air density, ρ , used in calculating q in Equations (3.6) and (3.7) is usually taken as the same value for screen and touchdown. The associated error is less than 1 per cent for height changes up to about 300 ft and so is likely to be significant only for landings of unpowered low L/D aircraft.

* "Screen" denotes the initial condition for the manoeuvre. The term is used for consistency with Reference 11 but does not imply any particular value of h_{screen} .

† The sign convention for γ means that, for landings, γ_{screen} takes a negative value.

3.2 Derivation of $[(D-F)/W]_a$ from Flight-test Measurements

For each landing a value of $[(D-F)/W]_a$, for use in Equation (3.5), is calculated from

$$\left[\frac{D-F}{W} \right]_a = \frac{2}{t_a(V_{screen} + V_{TD})} \left[h_{screen} + \frac{(V_{screen}^2 - V_{TD}^2)}{2g} \right], \quad (3.8)$$

or

$$\left[\frac{D-F}{W} \right]_a = \frac{1}{s_a} \left[h_{screen} + \frac{(V_{screen}^2 - V_{TD}^2)}{2g} \right] \quad (3.9)$$

and is a value applicable to the whole of the airborne manoeuvre. See Appendix A of Reference 11 for derivation of Equations (3.8) and (3.9).

3.2.1 Wind effects on measured data

Equation (3.8) uses quantities which either are measured relative to the air or are unaffected by the wind. (The time for the landing airborne manoeuvre is not affected by the presence of a uniform wind and wind gradients associated with flight-test conditions are unlikely to have a significant effect.) If $[(D-F)/W]_a$ is to be derived from Equation (3.9), the value of distance must be that appropriate to still-air conditions. For this purpose the reduction, Δs_a , in airborne distance due to a headwind component (either uniform or average value for the manoeuvre) may be determined from

$$\Delta s_a = \frac{s_a V_{W_{av}}}{\frac{1}{2}[V_{TD} + V_{screen}]}. \quad (3.10)$$

4. USE OF METHOD OF SECTION 3 TO REPRESENT FLIGHT-TEST MEASUREMENTS

4.1 Form of Relationship between $\Delta[C_{D-F}]$ and $\Delta[C_L^2]$

The analysis method of Section 3 has been applied to a large number of sets of landing measurements for a wide range of aircraft types – twelve examples are shown in Appendix A. Those results (together with physical reasoning) suggest that the simplest aerodynamically valid form of Equation (3.1), for relating values of $\Delta[C_{D-F}]$ and $\Delta[C_L^2]$, for any given set of landings, is

$$\Delta[C_{D-F}] = k_1 + k_2 \Delta[C_L^2], \quad (4.1)$$

where the coefficients k_1 and k_2 are determined empirically as illustrated in Sketch 1.1.

The method of Section 3 has been used successfully to represent landings with the initial condition as high as 100 ft (and, exceptionally, in excess of 1000 ft for one unpowered low L/D aircraft, see Figure A11) and as low as 30 ft above touchdown. For most cases, however, the height change was that associated with civil certification requirements, *i.e.* 50 ft for the majority of cases, 30 ft for a minority and 35 ft for a few (hence the use of the notation, h_{screen}). See Data Item No. 91032 (Reference 11) regarding definition of screen height in the context of aircraft civil certification.

4.2 Effect of Style of Landing Airborne Manoeuvre

The style of landing airborne manoeuvre executed has a considerable effect on the deduced value of $[(D-F)/W]_a$, on the relationship between $\Delta[C_{D-F}]$ and $\Delta[C_L^2]$ for the set of landings and thus on the values of k_1 and k_2 .

If a group of landings forms a reasonably consistent set – in terms of style of manoeuvres executed – the results from Equations (3.2) and (3.5) are most likely to result in a linear relationship as in Equation (4.1).

If a set of landings are very similar in style, and the ranges of values of $\Delta[C_L^2]$ and $\Delta[C_{D-F}]$ limited, it may not be possible to represent them in the form of Equation (4.1) and mean values of $\Delta[C_L^2]$ and $\Delta[C_{D-F}]$ must be used to characterise the measured data (although k_2 could be estimated using Figure 9 or 10 of Reference 11).

If a group of landings includes significantly different styles of airborne manoeuvre, the scatter in the plotted results is likely to reflect this. Such differences may be identified (and “exceptional” manoeuvres disregarded, if necessary) as follows.

- (i) If available, trace recordings of the landing airborne manoeuvres should be consulted.
- (ii) Landings “with no significant float” may be separated from those “with significant float” using the criteria of Figures 3 and 4 of Reference 11; see Figures A5, A10 and A12 here for examples.
- (iii) For landings “with no significant float” further distinctions can be made between different styles of airborne manoeuvre by applying the criteria of Section 5.1 and Sketch 5.1 of Reference 11. The effect of these criteria is to determine the extent and manner in which a particular airborne manoeuvre departs from a (straight line) continuation of the steady approach path.

4.3 Values of the Parameter k_1

For an unpowered aircraft (and assuming no aerodynamic configuration change occurs in the airborne manoeuvre) the value of k_1 in Equation (4.1) would be expected to be negative – corresponding to the decrease in drag (due to ground effect) while experiencing no change in airspeed ($\Delta[C_L^2] = 0$) between initial and final conditions.

For jet- and fan-engined aircraft almost all the cases examined can be represented by Equation (4.1) and show negative values of k_1 – see Figures A1 to A5. This indicates that the decrease in drag (due to ground effect) while experiencing no change in airspeed between initial and final conditions, is greater than the loss of thrust between the time the engine power is reduced (from the approach setting) and touchdown. In a few cases these effects nearly cancel and the line could be drawn through the origin.

For propeller-driven aircraft Equation (4.1) provides an adequate fit in all cases but instances have been found of both positive and negative values of k_1 – see Figures A6 to A10. This reflects the more rapid response of propellers (than jet and fan engines) to changes in power setting and the wide range of propeller thrust conditions corresponding to the flight-idle settings for different aircraft.

The influence of power-cut height can sometimes be seen from the plotted data – provided sufficient test points are available for a wide range of power-cut heights – see Figures A5 and A7.

A change in aerodynamic configuration during the airborne manoeuvre makes the value of k_1 more positive if the effect is to increase drag – see Figure A11.

5. METHOD FOR CALCULATING TOUCHDOWN SPEED

Touchdown speed, V_{TD} , for a particular landing can be calculated by the combined use of the energy equation and the method of representing flight-test data given in Sections 3 and 4. Sections 5.1 to 5.3 describe the procedure by reference to the need to equate the values of $[(D-F)/W]_a$ “required” to satisfy the energy equation and those “available” with a given style of landing manoeuvre for the aircraft concerned.

5.1 “Required” Value of $[(D-F)/W]_a$ to Perform a Particular Landing Airborne Manoeuvre

For an airborne manoeuvre for which the screen conditions are specified and the time, t_a , is known or can be estimated*, Equation (3.8) defines the “required” value of $[(D-F)/W]_a$ as a function of touchdown speed, *i.e.*

$$\left[\frac{D-F}{W} \right]_{a,required} = \frac{2}{t_a(V_{screen} + V_{TD})} \left[h_{screen} + \frac{(V_{screen}^2 - V_{TD}^2)}{2g} \right]. \quad (5.1)$$

5.2 “Available” Values of $[(D-F)/W]_a$ Corresponding to a Set of Flight-test Measurements

If the relationship between $\Delta[C_{D-F}]$ and $\Delta[C_L^2]$ for a set of landing airborne manoeuvre measurements is expressed in the form of Equation (4.1), it can be combined with Equations (3.2) and (3.5) to estimate “available” values of $[(D-F)/W]_a$ for similar landings of the same aircraft type, *i.e.*

$$\left[\frac{D-F}{W} \right]_{a,available} = \frac{k_1 + k_2 C_{L_{screen}}^2 \left[\frac{V_{screen}^4}{V_{TD}^4} - 1 \right] + [C_{L_{screen}} \tan(-\gamma_{screen})]}{C_{L_{screen}} \frac{V_{screen}^2}{V_{TD}^2}}. \quad (5.2)$$

5.3 Calculation of V_{TD} for Given Screen Conditions, Airborne Time and Style of Manoeuvre

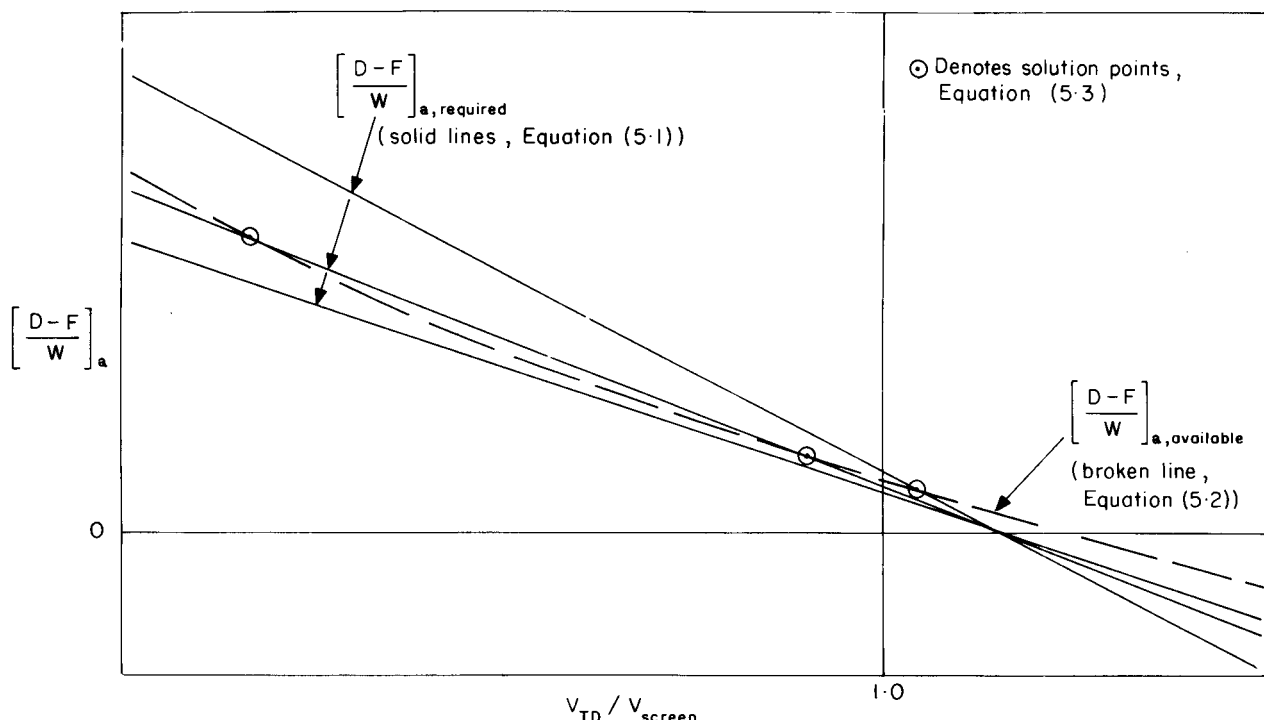
For given screen conditions (h_{screen} , V_{screen} , W , γ_{screen}) and a known or estimated* value of t_a , a particular style of airborne manoeuvre can be performed if the touchdown speed satisfies the condition

$$\left[\frac{D-F}{W} \right]_{a,required} = \left[\frac{D-F}{W} \right]_{a,available}. \quad (5.3)$$

The values of $[(D-F)/W]_a$ on the left and right hand sides of Equation (5.3) are defined by Equations (5.1) and (5.2) respectively and, for the specified airborne manoeuvre, each is a function of V_{TD} only. For machine calculations, solutions are best identified by seeking the value(s) of V_{TD} giving, say,

$$\left| \left[\frac{D-F}{W} \right]_{a,required} - \left[\frac{D-F}{W} \right]_{a,available} \right| < 0.00001. \quad (5.4)$$

* See Section 6.



Sketch 5.1 Procedure for calculating V_{TD} using “required” and “available” values of $[(D-F)/W]_a$

5.3.1 Observations on method for calculating touchdown speed

The method should be used to calculate values of V_{TD} for initial (screen) conditions which lie within or close to the ranges of values tested. Sketch 5.1 illustrates the method for calculating touchdown speed. The following observations may be made regarding the calculation procedure.

For given values of h_{screen} and V_{screen} , Equation (5.1) defines a unique relationship between $[(D-F)/W]_{a,required}$ and V_{TD}/V_{screen} for each value* of t_a . The three solid lines in Sketch 5.1 correspond to three such values of t_a .

For a given aircraft, style of landing airborne manoeuvre (i.e. k_1 , k_2 fixed) and screen conditions (V_{screen} , W , γ_{screen}), Equation (5.2) gives a unique relationship between $[(D-F)/W]_{a,available}$ and V_{TD}/V_{screen} . This is illustrated by the broken line in Sketch 5.1.

From the intersections of the solid and broken lines in Sketch 5.1 it can be seen that the condition

$$\left[\frac{D-F}{W} \right]_{a,required} = \left[\frac{D-F}{W} \right]_{a,available}$$

may be satisfied at a unique value of V_{TD}/V_{screen} , or at two values or not at all. (This conclusion applies to the practical range of values of V_{TD}/V_{screen} ; further intersections, i.e. solutions, are possible but of no practical significance here.)

* See Section 6.