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Low-speed longitudinal aerodynamic characteristics of aircraft in ground effect

Associated software: ESDUpac A7223



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LOW-SPEED LONGITUDINAL AERODYNAMIC CHARACTERISTICS OF AIRCRAFT IN GROUND EFFECT

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LOW-SPEED LONGITUDINAL AERODYNAMIC CHARACTERISTICS OF AIRCRAFT IN GROUND EFFECT

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
A	aspect ratio of wing, $b/\bar{c} = b^2/S$		
A_T	aspect ratio of tailplane, b_T^2/S_T		
a	lift-curve slope of aircraft in free air, $\partial C_L/\partial \alpha$	rad^{-1}	rad^{-1}
a_e	rate of change of tailplane lift coefficient in free air with elevator deflection, $\partial C_{LT}/\partial \eta$	rad^{-1}	rad^{-1}
a_T	lift-curve slope of tailplane in free air, $\partial C_{LT}/\partial \alpha_T$	rad^{-1}	rad^{-1}
b	wing span	m	ft
b_{eff}	effective wing span, see Equations (5.8) and (5.9)	m	ft
b_f	flap span	m	ft
b_T	tailplane span	m	ft
C_D	aircraft drag coefficient in free air, based on S		
C_{Dp}	aircraft profile drag coefficient in free air, based on S		
C_{Dv}	aircraft vortex drag coefficient in free air, based on S		
C_L	aircraft lift coefficient in free air, based on S		
C_{LT}	lift coefficient of tailplane in free air, based on S_T		
$C_{m^{1/4}}$	pitching moment coefficient of wing and body about quarter-chord point of aerodynamic mean chord of wing, based on S and $\bar{c}$, positive nose up		
$\bar{c}$	geometric (or standard) mean chord of wing, $S/b = b/A$	m	ft
h	height above ground of quarter-chord point of aerodynamic mean chord of wing, see Sketch 1.1	m	ft
h_T	height above ground of quarter-chord point of aerodynamic mean chord of tailplane, see Sketch 1.1 and Equation (5.4)	m	ft

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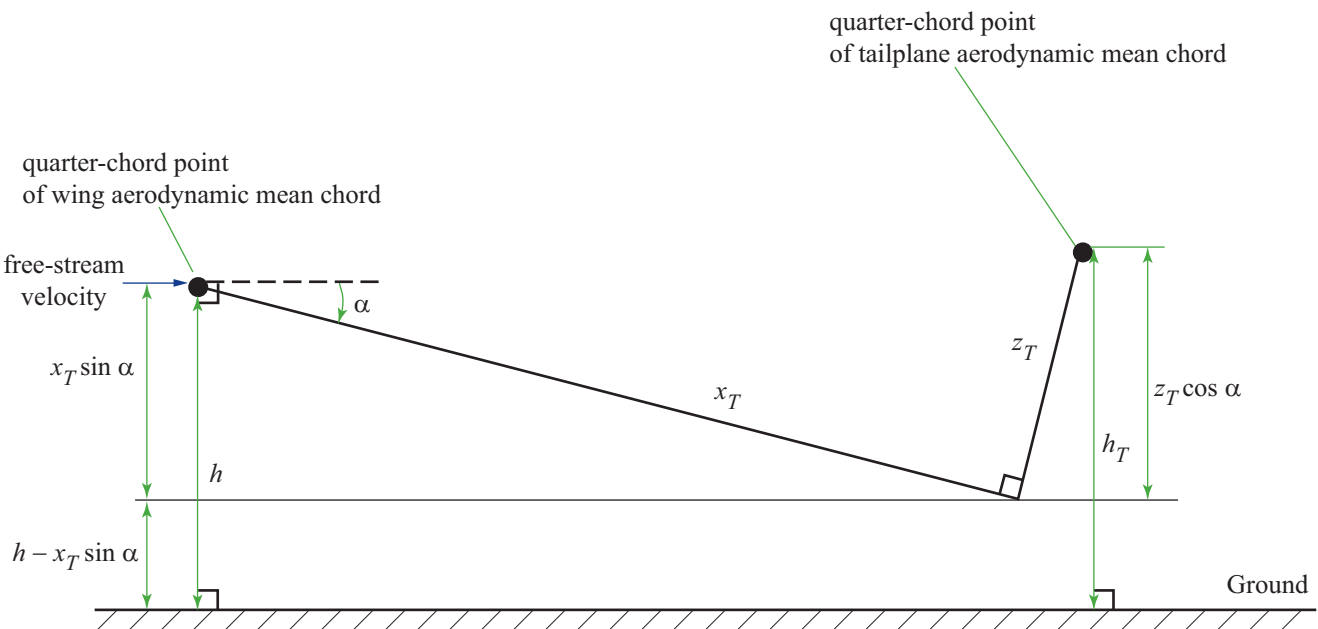
K	function for vortex drag due to flaps, from ESDU Aero F.02.01.08		
k_1	factor in Equations (5.8) and (5.9), see Figure 6a		
k_2	factor in Equation (5.9), see Figure 6b		
N	factor defined by Equation (3.3), see Figure 3		
r	factor in Equations (3.2), (3.4) and (3.5), see Figure 1		
S	gross planform area of wing	m ²	ft ²
S_T	gross planform area of tailplane	m ²	ft ²
t	maximum thickness/chord ratio of wing		
x_T	distance between quarter-chord points of mean aerodynamic chords of wing and tailplane, see Sketch 1.1	m	ft
z_T	distance of quarter-chord point of aerodynamic mean chord of tailplane above the quarter-chord point of aerodynamic mean chord of wing, measured normal to longitudinal axis of aircraft, see Sketch 1.1	m	ft
α	incidence of wing, see Sketch 1.1	rad	rad
α_T	incidence of tailplane	rad	rad
β	factor in Equation (5.3), see Figure 5		
ΔC_D	increment* in C_D due to ground at constant aircraft lift coefficient		
ΔC_L	increment* in C_L due to ground at constant incidence		
ΔC_{LT}	increment* in C_{LT} due to ground at constant aircraft lift coefficient		
ΔC_{Lt}	correction* in ΔC_L or δC_L for wing thickness, see Equation (3.5)		
ΔC_{Lt0}	value* of ΔC_{Lt} at $C_L = 0$, see Figure 4		
$\Delta \alpha$	increment* in α due to ground at constant aircraft lift coefficient	rad	rad
$\Delta \alpha_T$	increment* in α_T due to ground at constant aircraft lift coefficient	rad	rad
$\Delta \varepsilon$	increment* in ε due to ground at constant aircraft lift coefficient	rad	rad
$\Delta \eta$	increment* in η to trim aircraft in ground effect	rad	rad

*The sign convention of ΔC_L , $\Delta \alpha$ etc. is positive for an increase.

$(1 + \delta)$	vortex drag factor due to wing trailing vortices, from ESDU 74035 or ESDU 01007		
δC_L	incremental lift coefficient [*] , see Equation (3.2)		
$\delta \alpha$	incremental incidence [*] , see Equation (3.1)	rad	rad
ε	angle of downwash at tailplane in free air	rad	rad
ε_1	free-air correction of ε for tailplane position, see Equation (5.6)	rad	rad
η	elevator angle in free air	rad	rad
η_T	tail-setting angle, angle between tailplane chord and wing chord, see Equation (5.1)	rad	rad
λ	wing taper ratio, ratio of tip chord to centre-line chord		
σ	factor in Equations (3.1), (3.4) and (4.2), see Figure 1		
τ	factor in Equation (3.2), see Figure 2		
ϕ	factor in Equation (4.2), see Figure 1		

A prime (') denotes case with high-lift devices retracted *at the same aircraft incidence*.

^{*} The sign convention of ΔC_L , $\Delta \alpha$ etc. is positive for an increase.



Sketch 1.1 Incidence dependence of tailplane height above ground

2. INTRODUCTION

This Item provides means for estimating the changes in the lift curve, drag, tail lift and downwash from the wing of an aircraft due to ground effect in incompressible flow. It is assumed that the free-air conditions are known. The Item attempts to cover all aircraft within the limitations given below and with the exception of aircraft with pointed slender wings which are treated separately in ESDU 71007, (Reference 50).

Most of the problems of an aircraft flying in ground effect are dynamic, but the static treatment of the aerodynamics in this Item provides a satisfactory approximation for most practical situations, provided the region of the stall or high rates of change of incidence are avoided.

The curves and formulae are based on, or were developed from, the semi-empirical methods of Derivations 1, 2, 3, 12, 15 and 48, in which the ground is replaced by a mirror image of the aircraft and the real and image wings are replaced by vortex systems of equal and opposite strengths. The two-dimensional data in the development of the lift-curve method of Section 3 come principally from Derivations 2, 30, 42 and 45. The remaining Derivations listed in Section 7 provide supporting theoretical and experimental data.

In general, the Item considers the changes in the free-air conditions on approaching the ground at constant aircraft lift coefficient, and hence changing incidence. The method in Section 3, however, in which part of the ground-effect lift curve is constructed, allows the changes due to ground in incidence at constant lift coefficient or in lift coefficient at constant incidence to be found. A simplification in Equation (3.4) for conditions away from the stall gives ΔC_L without construction of the ground-effect lift curve. Unfortunately, no similar simplification is possible for $\Delta \alpha$.

The methods of Sections 3 to 5 were derived primarily for isolated wings and wing-body combinations. Hence, it would be more accurate to consider the Item as in general treating changes at constant lift of the aircraft wing-body combination and to allow for the tail separately. However, since the forces on the tail are relatively small, it is not necessary in most cases to estimate their separate contributions to the changes in total lift and drag and it is satisfactory to calculate the change in tailplane lift for pitching moment and trim only.

There are ground-induced changes in the pitching moment of the wing-body combination but these are not treated here and are usually small in comparison with the effect of the tail.

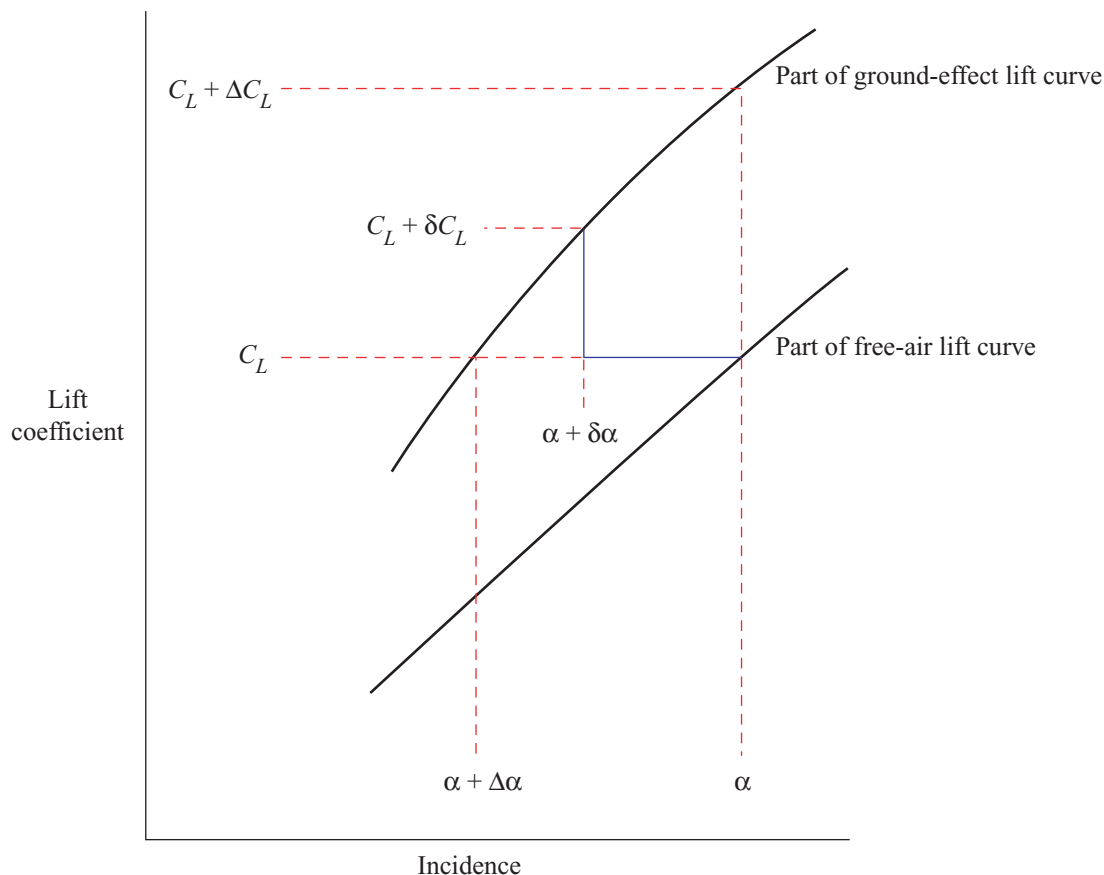
Note that, for the graphical information in Figures 1 to 6, curve fit equations are provided on the Figures.

The applicability and accuracy of the method are detailed in Section 6; Section 7 gives the Derivation and References, and a worked example is given in Section 8.

A program of the method is provided as ESDUpac A7223 and is described in Appendix A.

3. LIFT CURVE

The method of correcting the lift curve for ground effect is to combine a change in incidence $\delta\alpha$ at the given lift coefficient with a change in lift coefficient δC_L at the new incidence, see Sketch 3.1.



Sketch 3.1 Method of constructing lift curve in ground effect

From Derivations 1 and 2, the vertical induced velocity term, taken to be the contribution due to the trailing vortices of an image wing, gives rise to an incremental incidence

$$\delta\alpha = -\frac{\sigma C_L}{\pi A}, \quad (3.1)$$

where σ is presented in Figure 1 as a function of h/b .

From Derivation 48, the bound vorticity contributes

$$\delta C_L = r C_L \left[\frac{N}{(1 + \tau N C_L)^2} - 1 \right], \quad (3.2)$$

where r (a finite span factor from Derivation 2) is presented likewise in Figure 1, τ is given as a function of $h/\bar{c}$ in Figure 2 and N may be evaluated from

$$N = 1 + (N' - 1) \left[1 + \frac{2}{C_L} (C_{m^{1/4}} - C'_{m^{1/4}}) \right], \quad (3.3)$$

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as is generally most convenient, or taken from Figure 3. The parameter N' is the value of N for the wing with high-lift devices retracted at the same aircraft incidence and is represented by the curve of Figure 3 corresponding to $(C_{m^{1/4}} - C'_{m^{1/4}})/C_L = 0$, with an approximate expression for this curve also given in Figure 3. The parameters τ and N are factors in the correlation equation for two-dimensional ground effect as given in Derivation 2.

Whether it is required to find the change in incidence $\Delta\alpha$ due to ground for a given lift coefficient or the increment ΔC_L due to ground at a fixed incidence, the above method may be used with two or more starting points to construct the necessary part of the lift curve for some particular height. For the purpose of obtaining ΔC_L , if the stalling region is avoided and if it may be assumed that the free-air lift-curve slope a is constant over the range of incidence between α and $\alpha + |\delta\alpha|$, then Equations (3.1) and (3.2) reduce to

$$\frac{\Delta C_L}{C_L} = \frac{1}{1 - (a\sigma/\pi A)} \left\{ (a\sigma/\pi A) + r \left[\frac{N}{\{1 + \tau N C_L / [1 - (a\sigma/\pi A)]\}^2} - 1 \right] \right\}. \quad (3.4)$$

At fairly small ground heights ($h/\bar{c} < 1.0$) and small free-air lift coefficients, experiment indicates a need to correct the ground effect on lift for wing thickness. Unfortunately, these limited experimental data do not permit a reliable correlation, but potential flow calculations on aerofoil sections in Derivation 45 suggest that the thickness correction has a maximum when $C_L = 0$ and decreases with increasing C_L to a negligible level at a C_L of approximately 0.7. So, for the three-dimensional case, it is suggested that the approximate value of the thickness correction, ΔC_{Lt} , may be obtained from the expressions

$$\left. \begin{aligned} \Delta C_{Lt} &= r(1 - 1.4C_L)\Delta C_{Lt0} & (C_L < 0.7) \\ \Delta C_{Lt} &= 0 & (C_L \geq 0.7) \end{aligned} \right\} \quad (3.5)$$

where ΔC_{Lt0} is presented in Figure 4. This correction may be applied to δC_L from Equation (3.2) or ΔC_L from Equation (3.4).

4. DRAG

To find the change in drag due to the ground at constant aircraft lift coefficient it is necessary to divide up the drag coefficient in free air as

$$C_D = C_{Dp} + C_{Dv}, \quad (4.1)$$

where C_{Dp} and C_{Dv} are the profile and vortex drag contributions to C_D .

Based on the semi-empirical method of Derivation 15, which considers the Glauert-Hutchinson theoretical relations of Derivation 1 with the experimental data of Derivations 6 and 7, the change due to the ground is given by

$$\begin{aligned} \Delta C_D &= -\frac{\phi C_L}{\pi A} C_{Dp} - \left[\sigma - (1 - \sigma) \frac{\phi C_L}{\pi A} \right] C_{Dv} \\ &= -\frac{\phi C_L}{\pi A} C_D - \left[\sigma - (2 - \sigma) \frac{\phi C_L}{\pi A} \right] C_{Dv} \end{aligned} \quad (4.2)$$

via Equation (4.1).

The factors ϕ and σ are shown as functions of h/b in Figure 1 and the vortex drag coefficient is given by

$$C_{Dv} = \frac{(1+\delta)}{\pi A} C_L^2 + K^2 (C_L - C'_L)^2 \quad (4.3)$$

where $C_L - C'_L$ is the increment in wing lift coefficient due to the high-lift devices. The factor $(1+\delta)$ may be found from ESDU 74035 (Reference 51) for plain wings or via ESDU 01007 (Reference 52), and K is obtained from ESDU Aero F.02.01.08 (Reference 49).

5. TAIL LIFT AND DOWNWASH

In free air the angle of the tailplane to the stream incident upon it is

$$\alpha_T = \alpha + \eta_T - \varepsilon. \quad (5.1)$$

On approaching the ground at constant aircraft lift coefficient (or more accurately, at constant lift coefficient of the wing-body combination, see Section 2) this becomes

$$\alpha_T + \Delta\alpha_T = \alpha + \Delta\alpha + \eta_T - (\varepsilon + \Delta\varepsilon) \quad (5.2)$$

where $\Delta\alpha$ is the change in wing incidence, presented in Section 3, and $\Delta\varepsilon$ is the change in downwash at the tailplane due to the effect of the image wing, given by Equation (5.7). The tailplane lift is further affected by its image in the ground in the same way as the wing. Hence,

$$\Delta C_{LT} = a_T \Delta\alpha_T = a_T \left\{ \Delta\alpha - \Delta\varepsilon + \frac{\beta [C_{LT} + a_T (\Delta\alpha - \Delta\varepsilon)]}{\pi A_T} \right\} \quad (5.3)$$

where $a_T \beta [C_{LT} + a_T (\Delta\alpha - \Delta\varepsilon)] / \pi A_T$, the contribution from the image tailplane, is based on a simplification of the method of Section 3 for all practical values of C_{LT} (less than about 1.5); β is given as a function of h_T/b_T in Figure 5. Using the geometry in Sketch 1.1, h_T is given by

$$h_T = z_T \cos\alpha + h - x_T \sin\alpha \quad (5.4)$$

With the assumption that the changes in the pitching moment of the wing-body combination are negligible, the change in elevator angle required to trim the aircraft near the ground is given by

$$\Delta\eta = -\Delta C_{LT} / a_e. \quad (5.5)$$

The ground-induced change in the downwash at the tail can be considered in two steps. The known free-air downwash, ε , which corresponds to a wing incidence of α (and lift coefficient C_L), needs as the first step to be corrected (due to the change in height of the tailplane) to ε_1 , which is the downwash angle in free air again corresponding to C_L but measured at the position that the tail would occupy if the wing incidence were $\alpha + \Delta\alpha$.

$$\text{So,} \quad \varepsilon_1 = \varepsilon + \frac{d\varepsilon}{d\alpha} \Delta\alpha. \quad (5.6)$$