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Lift and rolling moment due to spoilers on wings at subsonic speeds with trailing-edge flaps undeployed

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LIFT AND ROLLING MOMENT DUE TO SPOILERS ON WINGS AT SUBSONIC SPEEDS WITH TRAILING-EDGE FLAPS UNDEPLOYED

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LIFT AND ROLLING MOMENT DUE TO SPOILERS ON WINGS AT SUBSONIC SPEEDS WITH TRAILING-EDGE FLAPS UNDEPLOYED

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
A	wing aspect ratio b^2/S_w		
a_{1w}	wing lift-curve slope, see Section 3.3.1.1	rad^{-1}	rad^{-1}
b	wing span, 2s	m	ft
C_L	wing lift coefficient, based on S_w		
ΔC_L	increment in C_L		
ΔC_{Ls}	increment in C_L due to part-span spoiler deployment on both port and starboard wing semi-spans, see Section 3.3.1		
ΔC_{LsF}	increment in C_L due to full-span spoiler deployment, see Section 3.3.1.1		
$\Delta C_{Ls\infty}$	two-dimensional value of ΔC_{Ls} , see Sections 3.2 and 3.3.1.1 and Figures 1a and 1b		
C_l	wing rolling moment coefficient, based on S_w and b , positive starboard wing panel down		
C_{ls}	value of C_l due to part-span spoiler deployment on either port or starboard semi-span, see Section 3.3.2		
$(C_{ls})_{ss}$	value of C_l due to either port or starboard semi-span spoiler deployment, see Section 3.3.2.1		
C_p	pressure coefficient		
c	local chord in streamwise direction	m	ft
c_{hs}	spoiler chord aft of flap-type spoiler hinge line, see Sketches 1.2b and 2.2	m	ft
c_k	value of c at crank station of a cranked wing, see Sketch 1.2a	m	ft
c_t	value of c at wing tip, see Sketches 1.1a and 1.2a	m	ft
c_0	value of c at plane of symmetry (centre line) for straight-tapered wing, see Sketch 1.1a	m	ft
$(c_0)_k$	value of c at plane of symmetry (centre line) for cranked wing, see Sketch 1.2a	m	ft
$\bar{c}$	standard (or geometric) mean chord, S_w/b	m	ft

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H	$h_{eff} + z_s$, see Section 3.2	m	ft
h	height of spoiler when deployed, see Sections 2.2 and 3.2 and Sketches 1.1b, 1.2b and 2.2	m	ft
h_{eff}	effective height of spoiler, <i>i.e.</i> deployment height of flat-plate type spoiler giving same lift increment, see Section 3.2	m	ft
k	correction factor for flap-type spoilers, see Section 3.2 and Figure 2		
k_a	correction factor applied to spanwise centre of pressure in Equation (3.13)		
M	freestream Mach number		
$R_{\bar{c}}$	Reynolds number, based on $\bar{c}$ and freestream properties		
S_{sptot}	total spoiler area, solid area plus area of slots, gaps and perforations, see Equations (2.1) and (2.6) for flat-plate and flap-type spoilers	m ²	ft ²
S_w	wing planform area	m ²	ft ²
s	wing semi-span, see Sketches 1.1a and 1.2a	m	ft
s_k	spanwise distance from centre-line to crank station of a cranked wing, see Sketch 1.2a	m	ft
w_b	body width, measured at widest point, see Sketches 1.1a and 1.2a	m	ft
w_s	spoiler width, measured along face of spoiler, see Sketches 1.1a and 1.2a	m	ft
x	streamwise distance from wing leading edge measured parallel to wing local chord, see Sketches 1.1b and 1.2b	m	ft
x_h	value of x at spoiler hinge position, see Section 2.2.2 and Sketches 1.2b and 2.2	m	ft
x_s	value of x at deployed spoiler trailing edge, see Section 2.2.2 and Sketches 1.1b, 1.2b and 2.2	m	ft
y	spanwise distance from wing centre line (positive starboard), see Sketches 1.1a and 1.2a	m	ft
z_s	upper-surface ordinate of wing section at x_s , see Sketches 1.1b, 1.2b and 2.2	m	ft
α	wing angle of attack measured from centre-line chord	deg	deg
β	$\sqrt{1 - M^2}$, Prandtl-Glauert compressibility factor		
δ_c	angle of spoiler datum line relative to chord in streamwise plane, see Section 2.2.2 and Sketch 2.2	deg	deg
δ_h	angle of flap-type spoiler deflection about hinge line, see Equation (2.2)	deg	deg

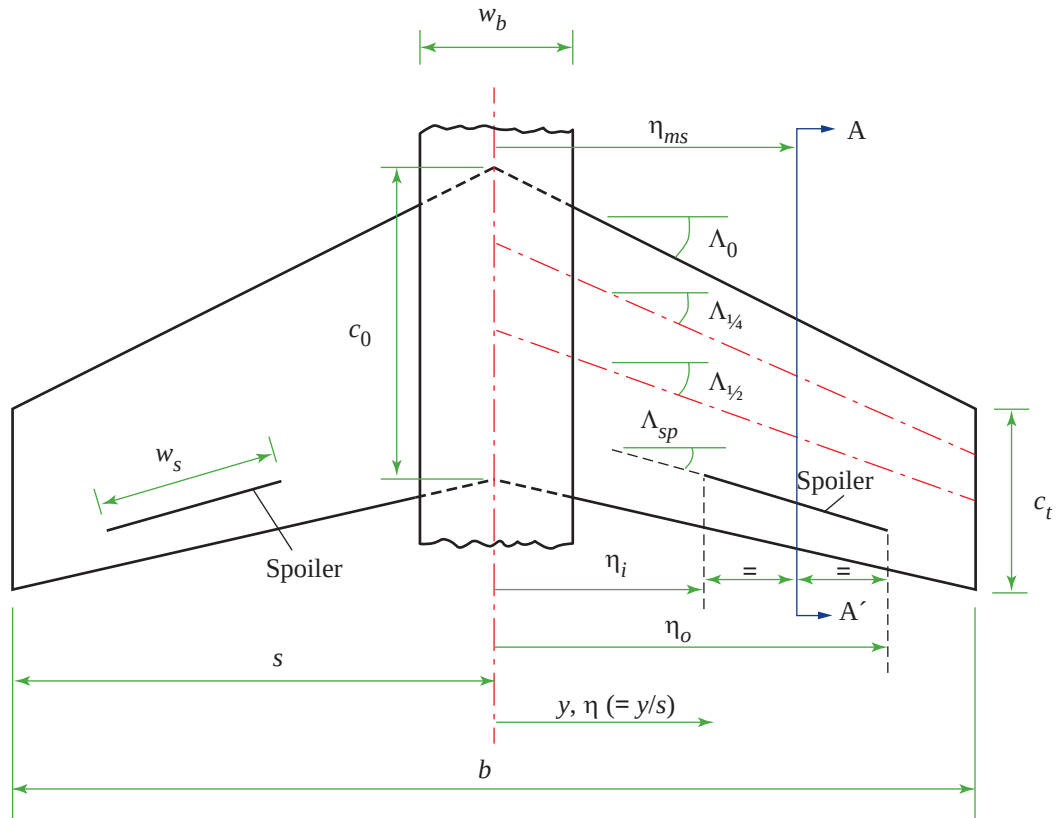
δ_s	angle of flap-type spoiler deflection in streamwise plane, see Sketches 1.2b and 2.2 and Equations (2.2) and (2.5)	deg	deg
η	spanwise distance from centre-line as fraction of semispan, y/s , see Sketches 1.1a and 1.2a		
η_i	value of η at inboard end of spoiler, see Sketches 1.1a and 1.2a, taken as inboard end of hinge-line for flap-type spoilers		
η_k	value of η at crank station, s_k/s , see Sketch 1.2a		
η_{ms}	value of η at mid-span of spoiler, see Section 2.3 and Equation (2.7) and Sketches 1.1a and 1.2a		
η_o	value of η at outboard end of spoiler, see Sketches 1.1a and 1.2a, taken as outboard end of hinge-line for flap-type spoilers		
$\bar{\eta}_{plan}$	value of η at spanwise centre of pressure position due to wing planform, see Section 3.3.2.1		
Λ_{sp}	spoiler sweep angle (sweepback is positive), see Sketches 1.1a and 1.2a, taken as sweep angle of hinge-line for flap-type spoilers	deg	deg
Λ_0	sweep angle of wing leading edge, see Sketches 1.1a and 1.2a	deg	deg
$\Lambda_{1/4}$	quarter-chord sweep angle of straight-tapered wing, see Sketch 1.1a	deg	deg
$\Lambda_{1/2}$	half-chord sweep angle of straight-tapered wing, see Sketch 1.1a	deg	deg
λ	taper ratio, c_t/c_0		
σ	porosity, ratio of spoiler open area to spoiler total area (see Sections 3.2 and 4.5)		
Φ_{ps}	$\Phi_{\eta_o} - \Phi_{\eta_i}$, part-span correction factor for lift, see Section 3.3.1.2		
Φ_{η}	part-span parameter for lift, see Section 3.3.1.2		
Φ_{η_i}	value of Φ_{η} with $\eta = \eta_i$, see Section 3.3.1.2		
Φ_{η_o}	value of Φ_{η} with $\eta = \eta_o$, see Section 3.3.1.2		
Ψ_{ps}	$\Psi_{\eta_o} - \Psi_{\eta_i}$, part-span correction factor for rolling moment, see Section 3.3.2.2		
Ψ_{η}	part-span parameter for rolling moment, see Section 3.3.2.2		
Ψ_{η_i}	value of Ψ_{η} with $\eta = \eta_i$, see Section 3.3.2.2		
Ψ_{η_o}	value of Ψ_{η} with $\eta = \eta_o$, see Section 3.3.2.2		

Subscript

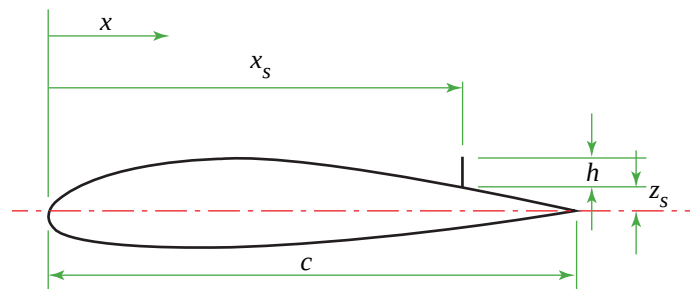
$()_{\eta_{ms}}$ value at η_{ms}

Port semi-span

Starboard semi-span



a) Planform geometry

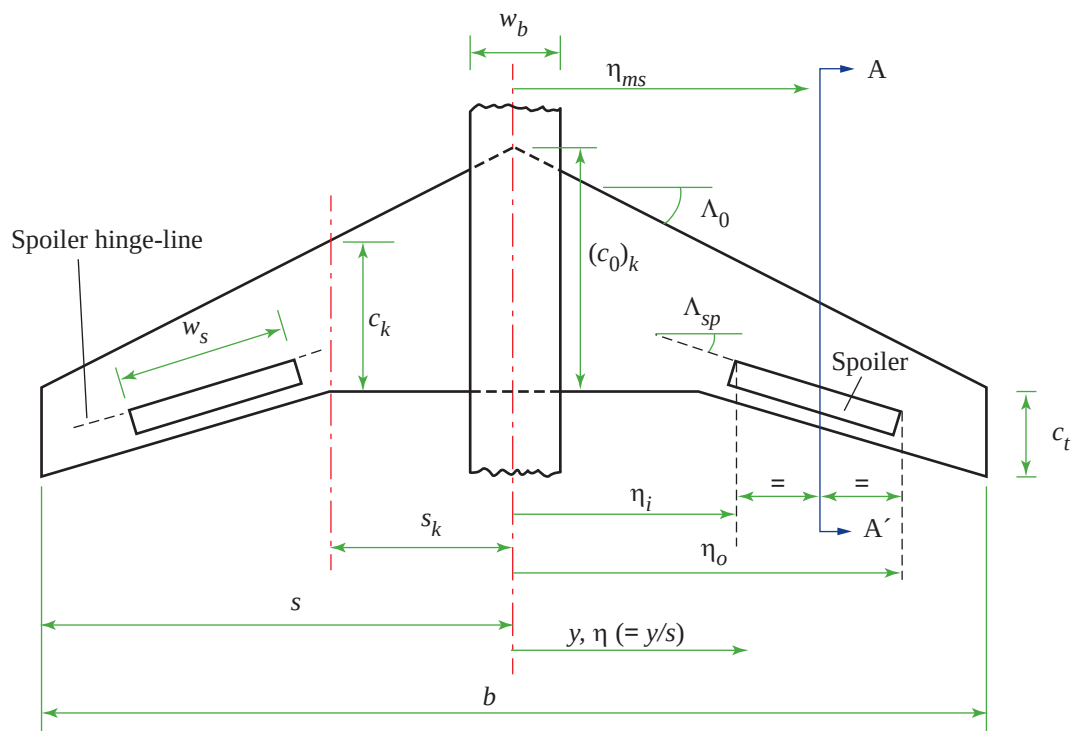


b) Section A - A' (spoiler mid-span section)

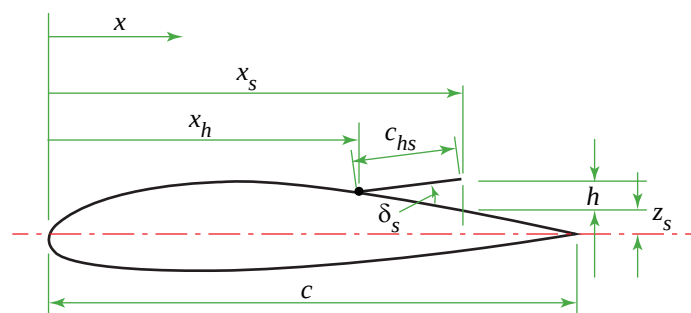
Sketch 1.1 Straight-tapered wing with flat-plate spoiler

Port semi-span

Starboard semi-span



a) Planform geometry



b) Section A – A' (spoiler mid-span section)

Sketch 1.2 Single crank wing with flap-type spoiler

2. INTRODUCTION

Spoilers may be used on both upper and lower surfaces of wings, but they are used most frequently on the upper surface. A “spoiler” attached to the upper surface of a wing will cause the flow to separate, literally “spoiling” the flow, and usually resulting in a loss of lift and increase in drag. The spoiler is usually a device that can be actuated very quickly. These three attributes, *i.e.* loss of lift, increase in drag and rapid actuation, lead to a variety of uses or potential uses on aircraft. These include use

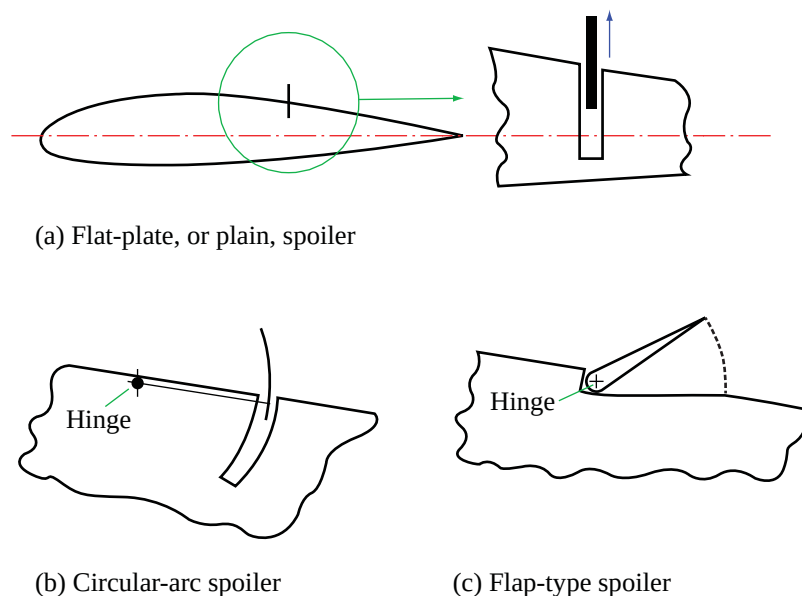
- (a) as roll control,
- (b) for lift dumping,
- (c) as an airbrake,
- (d) for direct lift control (DLC), *i.e.* controlling lift without change of attitude,
- (e) for load alleviation,
- (f) as a means of reducing the hazard of trailing vortices to following aircraft.

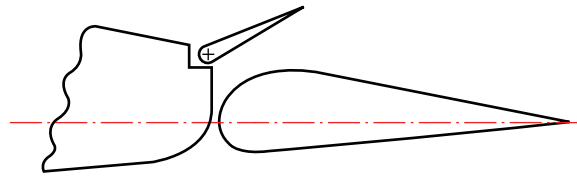
Spoilers also have other, non-aeronautical uses, such as the prevention of overspeeding of wind turbines.

Spoilers may be placed at any chordwise position, have various spanwise extents, and be used in isolation or in combination with flaps and ailerons. The parameters of interest will depend upon the particular application. In addition to steady lift, drag and rolling moment there may be interest in the time varying characteristics (for (e) above), in pitching and yawing moments, and in the hinge moments and power required for actuation. This Item presents a method for predicting the lift and rolling moment due to upper-surface spoiler deployment, but without deployed trailing-edge flaps, the effects of which are covered in ESDU 14005 (Reference 50). The method is based on information contained in Derivations 1 to 33. Additional useful descriptive or supplementary information is contained in References 34 to 49.

2.1 Types of Spoiler

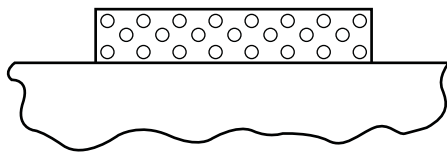
Various types of spoiler are illustrated on the upper surface of an aerofoil or wing in Sketch 2.1.



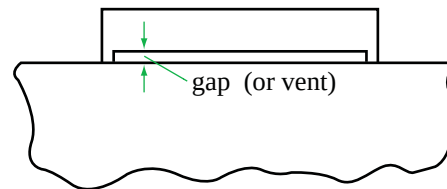


(d) Spoiler with lower-surface venting

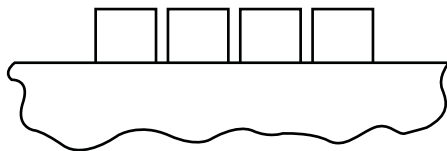
Spoiler face variations



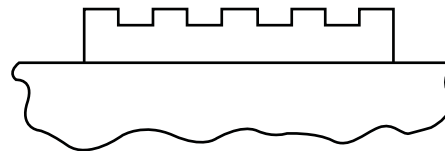
(e) Perforated spoiler



(f) Spoiler with hinge-line gap



(g) Segmented spoiler



(h) Spoiler with notched edge

Sketch 2.1 Types of spoiler

The flat-plate, perpendicular to the surface (a) is geometrically the simplest, and often used in wind-tunnel testing.

The circular arc (b) approximates to the flat plate, rotation is more convenient than the sliding motion of the flat plate, but a deep cut through the wing structure is still required.

The flap-type spoiler (c) is the one usually used on aircraft. Other more complicated forms of spoilers include venting of air from the lower surface of the wing (d), or the use of air jets.

The non-linear and buffeting characteristics of spoilers can often be improved by the use of some porosity, either in the form of a perforated surface (e), hinge-line gap (or vent) (f), or segmentation (g). Trailing-edge notching (h) has also been tried.

The method outlined in this Item is based on the flat-plate type spoiler, with factors to incorporate flap-type spoilers and porosity. Neither venting from the lower surface, nor the combination of spoiler with trailing-edge flap deployment, is considered here, but see ESDU 14005 (Reference 50) which treats those topics.

2.2 Spoiler Geometries

Since the circular arc spoiler geometry approximates the flat-plate spoiler geometry it is treated in this Data Item in the same way as a flat-plate spoiler. The flat-plate spoiler and flap-type spoiler are considered in Sections 2.2.1 and 2.2.2 respectively.

2.2.1 Flat-plate spoiler

The spanwise positions of the inner and outer extents of a flat-plate spoiler are η_i and η_o respectively, see Sketch 1.1a.

Flat-plate spoilers are aligned perpendicular to the section chord line. The spoiler deployment height, h , is the distance from the top of the deployed spoiler to the aerofoil contour and z_s is the section ordinate of the upper surface at the spoiler chordwise position, see Sketch 1.1b. The spoiler sweep angle, Λ_{sp} , for a flat-plate spoiler is also shown in Sketch 1.1a, with sweepback angles measured positive. For some tapered unswept wings the spoiler could be swept forward and in this case Λ_{sp} has a negative value. For flat-plate spoilers x_s is the streamwise distance from the aerofoil leading-edge to the spoiler.

The total area, S_{sptot} , of a deployed flat-plate rectangular spoiler is

$$S_{sptot} = hw_s, \quad (2.1)$$

which is the solid plus open areas of the spoiler (see Sketches 2.1(e) to 2.1(h)), where w_s is the spoiler width, see Sketch 1.1a.

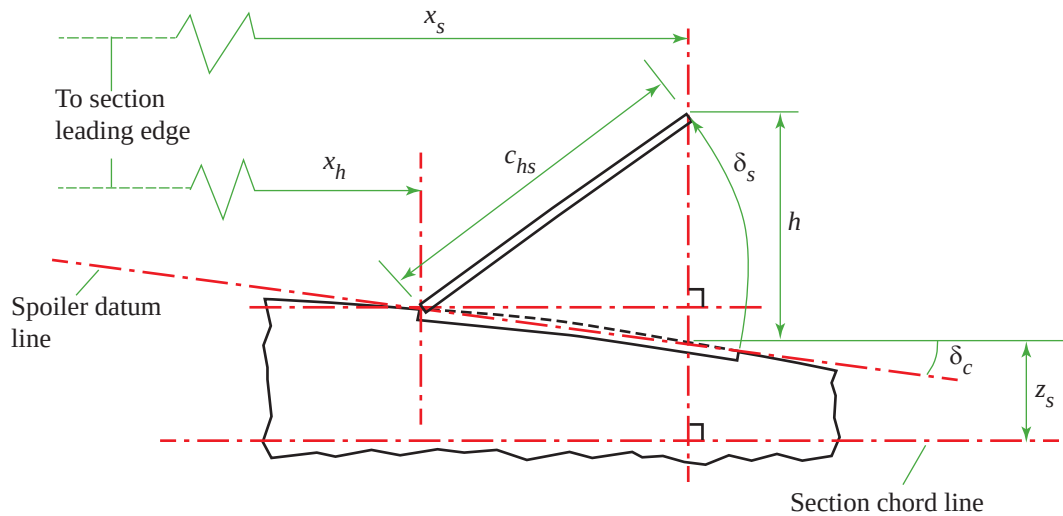
2.2.2 Flap-type spoiler

The spanwise positions of the inner and outer extents of a flap-type spoiler (η_i and η_o) are taken at the spoiler hinge line, see Sketch 1.2a.

For flap-type spoilers the streamwise distance, x_s , from the aerofoil leading-edge to the spoiler trailing-edge is dependent on the spoiler deflection angle. A spoiler datum line is defined in this Item as a straight line connecting the spoiler hinge to the spoiler trailing edge when the spoiler is undeployed, see Sketch 2.2. The spoiler deflection angles δ_h and δ_s are then measured from that datum. The deflection δ_h is a rotation about the hinge line and δ_s is a rotation in the streamwise plane, see Sketch 2.2. The angle of the spoiler datum line relative to the chord line is δ_c in the streamwise plane, see Sketch 2.2.

For flap-type spoilers c_{hs} is the spoiler chord aft of the hinge and the spoiler sweep angle, Λ_{sp} , is the sweep of the hinge line, see Sketch 1.2a. Spoiler sweepback angles are measured positive, consequently spoiler sweep forward angles have negative values. For most practical spoiler and wing section geometries δ_c is small enough to be neglected and therefore from geometric considerations the spoiler deflection angle, δ_s , in the streamwise vertical-plane is

$$\delta_s \approx \tan^{-1} \left[\tan \delta_h \cos \Lambda_{sp} \right]. \quad (2.2)$$



Sketch 2.2 Deployed flap-type spoiler geometry (streamwise section at spoiler mid-span)

For flap-type spoilers the streamwise distance, x_s , from the aerofoil leading-edge to the spoiler trailing edge is dependent on the spoiler deflection angle.

From the geometry in Sketch 2.2 and since δ_c is small enough to be neglected, x_s is obtained to a good approximation using

$$x_s \approx x_h + c_{hs} \cos \delta_s, \quad (2.3)$$

where x_h is the streamwise distance from the aerofoil leading-edge to the spoiler hinge line.

For flap-type spoilers h is the distance from the spoiler trailing-edge to the aerofoil contour measured perpendicular to the section chord, see Sketch 2.2. Since δ_c is small enough to be neglected the spoiler deployment height, h , is obtained to a good approximation using

$$h \approx c_{hs} \sin \delta_s. \quad (2.4)$$

Analysis indicates that for $\delta_c \leq 10^\circ$ Equations (2.3) and (2.4) provide very good approximations of x_s and h respectively. Most practical spoiler and wing section geometries have $\delta_c \leq 10^\circ$.

At the chordwise position x_s , the section ordinate of the upper surface is z_s and its value is dependent on the deflection angle of the flap-type spoiler. Rearranging Equation (2.4) gives the spoiler deflection angle in terms of h , so that

$$\delta_s \approx \sin^{-1} \left(\frac{h}{c_{hs}} \right). \quad (2.5)$$

The total area, S_{sptot} , of a flap-type rectangular spoiler is

$$S_{sptot} = c_{hs} w_s, \quad (2.6)$$

which is the solid plus open areas of the spoiler (see Sketches 2.1(e) to 2.1(h)), where w_s is the spoiler width, see Sketch 1.2a.

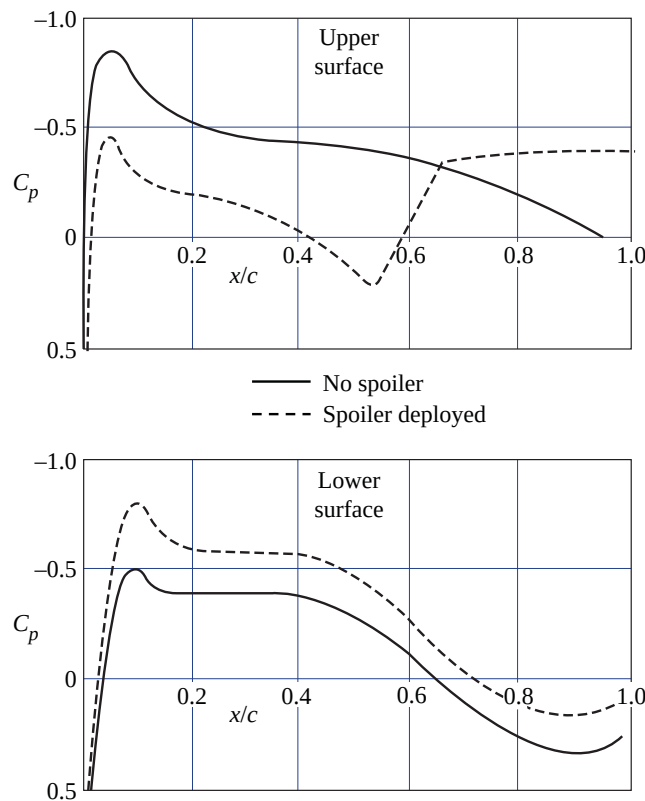
2.3 Wing Section at Spoiler Mid-span

The wing section at the mid-span of the spoiler is defined in a streamwise vertical plane, see Sketches 1.1a and 1.2a. Its spanwise location, η_{ms} , is the mid point between the inner and outer spanwise extents of the spoiler, *i.e.*

$$\eta_{ms} = \frac{\eta_o + \eta_i}{2}. \quad (2.7)$$

2.4 Spoiler Characteristics

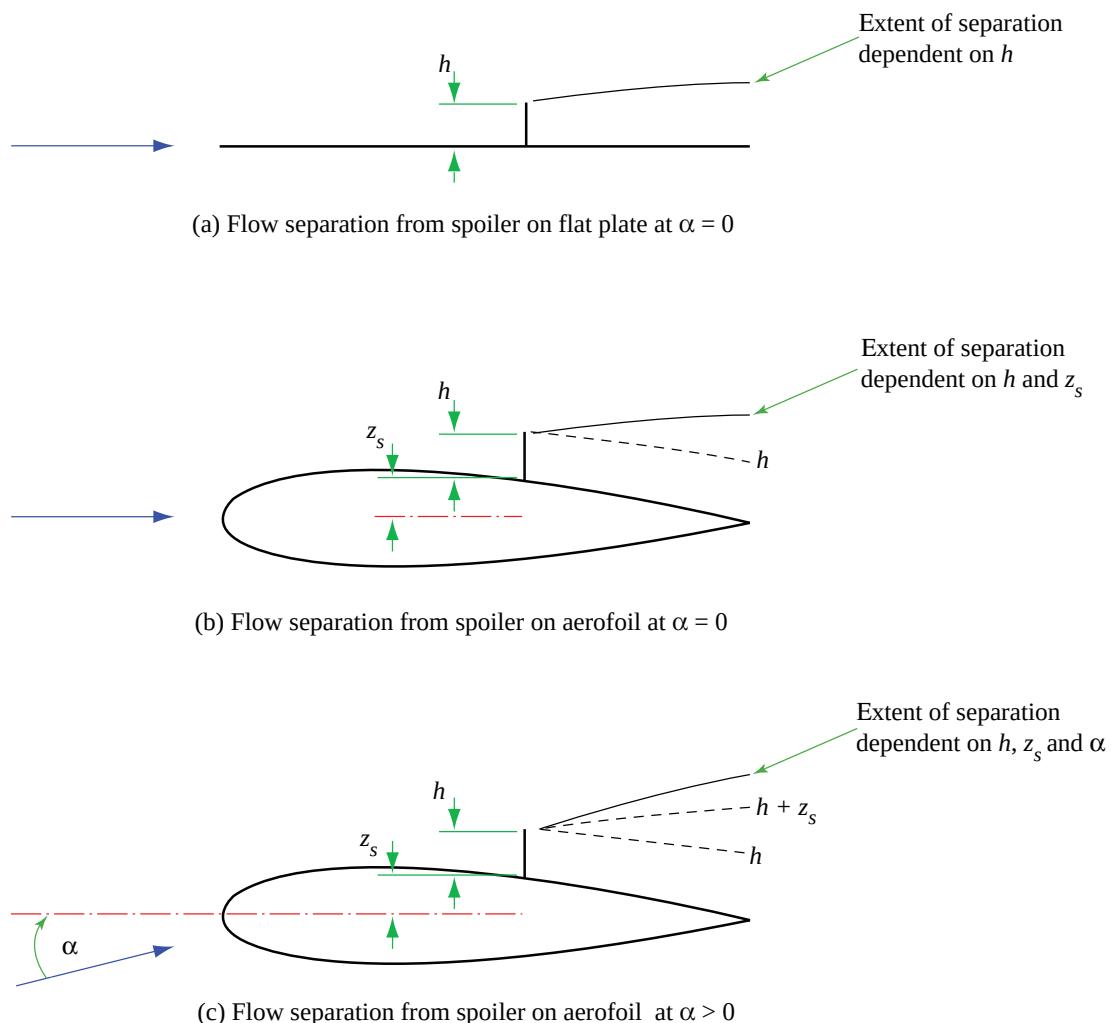
The action of a spoiler on an aerofoil is to create separated flow. The extent of the separation in a two-dimensional flow depends upon the deployment height, h , and shape of the spoiler, its chordwise position, the aerofoil section and angle of attack α , Mach number, and Reynolds number. With finite wings the separation will also depend upon the wing planform (aspect ratio, taper ratio, sweep) and the spanwise position and extent of the spoilers. The separation may extend upstream of the spoiler, and the downstream separation may re-attach for small deployment heights and forward spoiler positions. The boundary for the free-stream flow is hence changed, the free stream is effectively displaced from the original surface and thus the aerofoil generates a different lift and has a different zero-lift angle of attack. The distribution of pressure coefficient, C_p , around the aerofoil is changed, typically as shown in Sketch 2.3. Ahead of the spoiler pressure is increased resulting in a download; behind the spoiler pressure is decreased giving an upward force; on the lower surface pressure is decreased, again giving a download. The loss of lift can come as much from the lower surface as the upper.



Sketch 2.3 Typical pressure distribution with spoiler

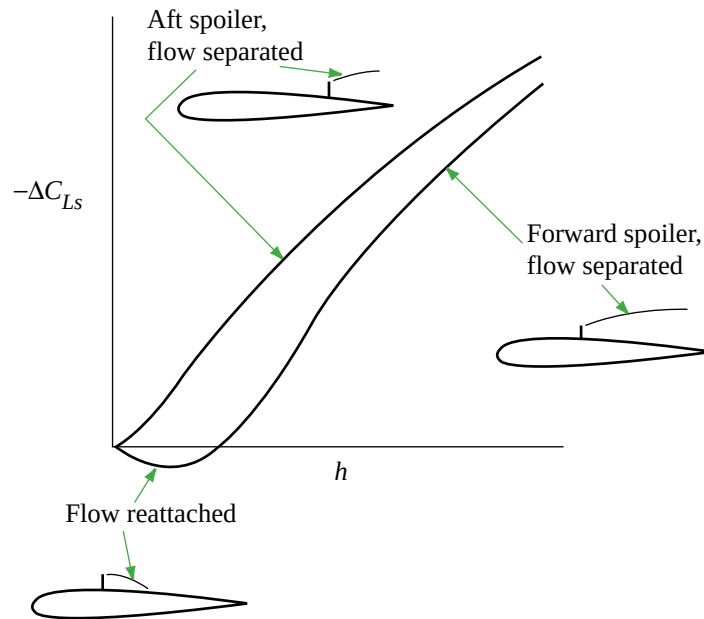
The depth of the region of separated flow at the aerofoil trailing-edge is in part related to the spoiler deployment height, and in part to the aerofoil shape and angle of attack, see Sketch 2.4. The extent of flow separation on a spoiler attached to a flat-plate at zero angle of attack is dependent on spoiler deployment height, h , see Sketch 2.4 (a). When the spoiler is attached to an aerofoil at zero angle of attack the extent of flow separation is dependent on both h and z_s . The dashed line in Sketch 2.4(b) indicates the extent of separation due to the effect of h and the continuous line indicates the extent due to the combined effects of h and z_s . The extent of flow separation on a spoiler attached to an aerofoil at varying angles of attack is dependent on h and z_s and α . The lower dashed line in Sketch 2.4(c) denotes the extent of separation due to the effect of h and the upper dashed line denotes the extent due to the combined effects of h and z_s . The continuous line in Sketch 2.4(c) indicates the extent of flow separation due to the combined effects of h and z_s and α .

The zero-lift angle of attack is dependent on the depth of the region of separated flow at the aerofoil trailing-edge. The change in zero-lift angle of attack can be correlated against a total height equivalent to the spoiler deployment height plus the section ordinate at the spoiler position (as in Derivation 14). The variation due to angle of attack can be related to spoiler chordwise position.



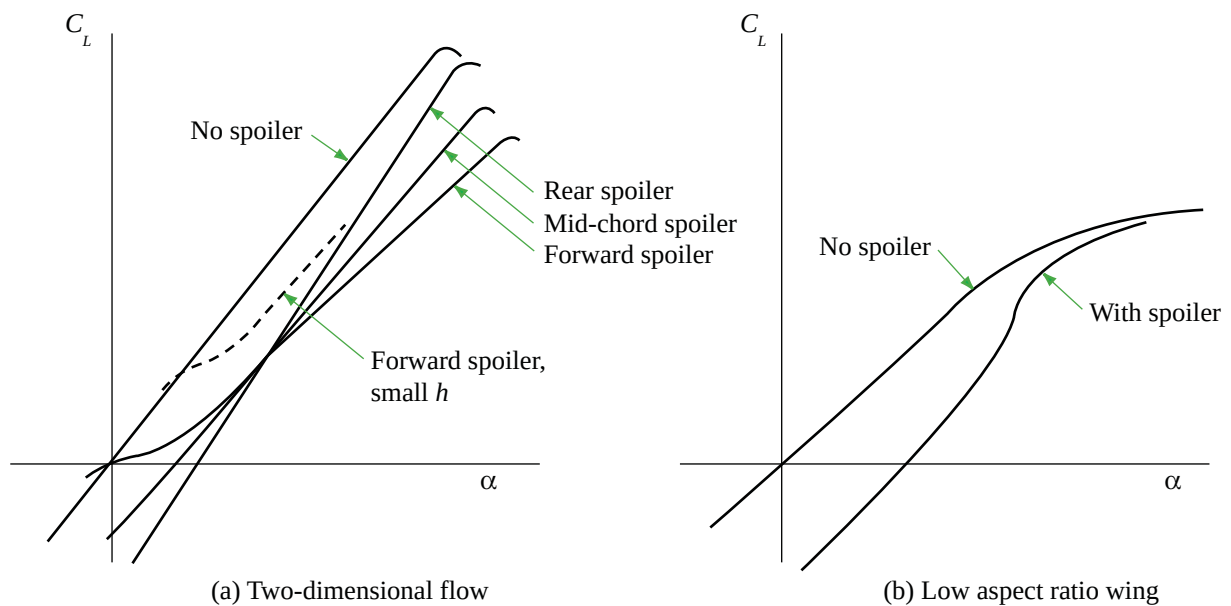
Sketch 2.4 Parameters affecting extent of flow separation

Typical variations of lift coefficient increment due to spoiler deployment, ΔC_{L_s} , (usually negative, i.e. a decrement) are shown in Sketch 2.5. The variation of lift with deployment height is usually non-linear, and particularly so when the flow re-attaches, or when a trailing-edge flap is deployed.



Sketch 2.5 Lift increment

Typical variations of lift with angle of attack for various spoiler deployment heights and spoiler positions are shown in Sketches 2.6(a) and (b). Note in particular that the lift curve with fixed spoiler deployment height is essentially linear over part of its range, bounded at low angles of attack by conditions that allow the flow to re-attach, and at high angles of attack by the approach of stall. Note also that the lift-curve slope varies with the chordwise position of the spoiler and that the low angle of attack cut-off occurs at different angles of attack for different spoiler deployment heights.



Sketch 2.6 Typical lift characteristics

3. METHOD

This Data Item presents an empirical method for predicting the lift coefficient increment (usually negative, *i.e.* a decrement) and rolling moment coefficient due to spoiler deployment on the upper surface at subsonic speeds. The two-dimensional lift characteristics of the section at the mid-span position of the spoiler are first determined, and the corresponding three-dimensional lift and rolling moment characteristics are then deduced.

3.1 Wing Section at Spoiler Mid-span

The method requires knowledge of spoiler and wing section geometries at the mid-span position of the spoiler, defined in Section 2.3. The spanwise position and chord of the wing section at the mid-span of the spoiler are obtained using Sections 3.1.1 and 3.1.2, respectively.

3.1.1 Spanwise position of wing section at spoiler mid-span, η_{ms}

The spanwise position of the wing section at the spoiler mid-span is given by Equation (2.7), *i.e.*

$$\eta_{ms} = \frac{\eta_o + \eta_i}{2}.$$

3.1.2 Chord of wing section at spoiler mid-span

Equations (3.1) to (3.3) below give the basic chord, c , for a wing section in a streamwise direction at any given spanwise position η for straight-tapered wings and wings with a single crank. The chord of the wing section at the mid-span position of the spoiler can therefore be obtained using these equations with $\eta = \eta_{ms}$.

For a straight-tapered wing

$$c = c_0 - \eta(c_0 - c_t), \quad (3.1)$$

where c_0 and c_t are the wing centre-line chord and tip chord respectively, see Sketch 1.1a.

For a wing with a single crank

$$c = (c_0)_k - \frac{\eta}{\eta_k}[(c_0)_k - c_k] \quad \text{for} \quad 0 \leq \eta \leq \eta_k, \quad (3.2)$$

$$\text{and} \quad c = c_k - \left(\frac{\eta - \eta_k}{1 - \eta_k} \right) [c_k - c_t] \quad \text{for} \quad \eta_k \leq \eta \leq 1.0, \quad (3.3)$$

where $(c_0)_k$ is the centre-line chord, c_k , is the chord at the crank station and η_k is the spanwise position of the crank station, see Sketch 1.2a.

3.2 Two-dimensional Characteristics at η_{ms}

The spoiler characteristics illustrated in Sketch 2.6 show the lift coefficient increment varying linearly over much of the angle of attack range. In the present analysis a linear variation of lift coefficient increment, ΔC_L , with angle of attack is assumed, with limitations as outlined in Section 4.6.

The various aerofoil section and spoiler parameters are obtained at the mid-span position of the spoiler, *i.e.* η_{ms} .

Figures 1a and 1b* give the two-dimensional lift coefficient increment, $\Delta C_{L\infty}$, at low speed at $\alpha = 0$ and 10° respectively. The lift coefficient increment is given as a function of spoiler chordwise position x_s/c and the parameter H/c , where

$$H = h_{eff} + z_s, \quad (3.4)$$

in which z_s is the section ordinate at the spoiler position (see Sections 2.2.1 and 2.2.2) and h_{eff} is an effective spoiler height, where

- (i) for a flat-plate spoiler with no porosity

$$h_{eff} = h \text{ (the spoiler deployment height),} \quad (3.5)$$

- (ii) for a flat-plate spoiler with porosity of the form illustrated in Sketches 2.1(e) to 2.1(h)

$$h_{eff} = h(1 - \sigma), \quad (3.6)$$

where σ is the total open area (of slots/gaps/perforations) as a fraction of the total (solid plus open) area of the spoiler, S_{sptot} , see Equation (2.1),

- (iii) for a flap-type spoiler with no porosity

$$h_{eff} = hk, \quad (3.7)$$

where k is a function of spoiler deflection angle, given in Figure 2, and

- (iv) for a flap-type spoiler with porosity of the form illustrated in Sketches 2.1(e) to 2.1(h)

$$h_{eff} = hk(1 - \sigma), \quad (3.8)$$

and the value of S_{sptot} used to obtain σ is obtained using Equation (2.6).

3.3 Three-dimensional Characteristics

The method is applicable to both straight-tapered and cranked wing geometries. If the wing is cranked, an equivalent straight-tapered wing planform is required, see ESDU 76003 (Derivation 25). Equations given in ESDU 07002 (Derivation 32) can be used to construct the equivalent straight-tapered wing geometry for a wing with a single crank. Two worked examples are given in Section 6. Examples 1 and 2 illustrate the use of the method for a straight-tapered wing and a cranked wing respectively.

Section 3.3.1 evaluates the lift-coefficient increment due to deployed spoilers on both the port and starboard wing semi-spans. Section 3.3.2 evaluates the rolling moment coefficient due to a deployed spoiler on either the port or starboard semi-span.

* Figures 1a and 1b were constructed using data obtained from wind-tunnel tests where the experimental set-up allowed two-dimensional flow to be approximated.

3.3.1 Lift coefficient increment due to deployed spoilers, ΔC_{Ls}

This section presents an empirical method for predicting the increment in lift coefficient due to deployed spoilers on the upper surfaces of both the port and starboard wing semi-spans. The lift coefficient increment, ΔC_{Ls} , due to spoilers deployed on both semi-span wing panels is

$$\Delta C_{Ls} = \Phi_{ps} \Delta C_{LsF}, \quad (3.9)$$

where ΔC_{LsF} is the lift coefficient increment due to a full-span spoiler and Φ_{ps} is a part-span factor for spoiler lift. A full-span spoiler is defined in this Data Item as extending from the wing centre-line ($\eta = 0$) to the wing tip ($\eta = 1.0$) on **both** port and starboard semi-spans.

3.3.1.1 Lift coefficient increment due to full-span spoiler, ΔC_{LsF}

The lift coefficient increment, ΔC_{LsF} , due to a full-span spoiler on a wing is obtained by scaling the two-dimensional lift coefficient increment, $\Delta C_{Ls\infty}$, in proportion to the ratio of wing lift-curve slope to the nominal two-dimensional value 2π per radian. Hence,

$$\Delta C_{LsF} = \frac{\Delta C_{Ls\infty}}{2\pi} a_{1w}, \quad (3.10)$$

where a_{1w} is the wing lift-curve slope which is obtained using ESDU 70011 (Derivation 21).

Values of ΔC_{LsF} are obtained for $\alpha = 0$ and $\alpha = 10^\circ$ by using Equation (3.10) with values of $\Delta C_{Ls\infty}$ obtained from Figures 1a and 1b. As for the two-dimensional characteristics, a linear variation of ΔC_{LsF} with angle of attack is assumed, with limitations as outlined in Section 4.6.

3.3.1.2 Part-span factor for spoiler lift, Φ_{ps}

The part-span factor for spoiler lift, Φ_{ps} , allows for a part-span spoiler and is determined using

$$\Phi_{ps} = \Phi_{\eta o} - \Phi_{\eta i}, \quad (3.11)$$

where $\Phi_{\eta o}$ is the value of a part-span parameter for lift, Φ_{η} , with $\eta = \eta_o$ and $\Phi_{\eta i}$ is the value of Φ_{η} with $\eta = \eta_i$. Values of $\Phi_{\eta i}$ and $\Phi_{\eta o}$ are obtained from Figures 4a and 4b at positions η_i and η_o . Figures 4a and 4b were constructed using wind-tunnel test data for flat-plate spoilers, see Section 5 of ESDU TM 172 (Derivation 33). These figures are applicable to both flat-plate and flap-type spoilers, see Section 4.

3.3.2 Rolling moment coefficient due to a deployed spoiler, C_{ls}

This section presents an empirical method for predicting the rolling moment coefficient, C_{ls} , due to a spoiler deployed on the upper surface of either the port or starboard wing semi-span. The two worked examples given in Section 6 illustrate the use of the method. Example 1 predicts C_{ls} due to a spoiler deployed on the starboard semi-span of a straight-tapered wing and Example 2 predicts C_{ls} due to a spoiler deployed on the port semi-span of a cranked wing.

The rolling moment coefficient, C_{ls} , due to a deployed spoiler on either the port or starboard semi-span is obtained using

$$C_{ls} = \Psi_{ps}(C_{ls})_{ss}, \quad (3.12)$$

where $(C_{ls})_{ss}$ is the rolling moment coefficient due to a semi-span spoiler and Ψ_{ps} is a part-span factor for spoiler rolling moment. A semi-span spoiler is defined in this Data Item as extending from the wing centre-line ($\eta = 0$) to the wing tip ($\eta = 1.0$) on either the port or starboard semi-spans.

3.3.2.1 Rolling moment coefficient due to semi-span spoiler, $(C_{ls})_{ss}$

The rolling moment coefficient, $(C_{ls})_{ss}$, due to a semi-span spoiler on the starboard wing panel is

$$(C_{ls})_{ss} = -\frac{\Delta C_{LsF}}{4} k_a \bar{\eta}_{plan}, \quad (3.13)$$

where $\bar{\eta}_{plan}$ is the spanwise centre of pressure position due to wing planform geometry and k_a is a correction factor applied to $\bar{\eta}_{plan}$. The rolling moment coefficient, $(C_{ls})_{ss}$, due to a semi-span spoiler on the port wing panel is obtained using Equation (3.13) but with opposite sign. Equation (3.13) was developed from Equations (A3.1) and (A4.1) in Appendix A.

In ESDU TM 172 $\bar{\eta}_{plan}$ is defined as the component of wing spanwise centre of pressure due to the wing planform without any geometric or aerodynamic twist*. Figures 6a to 6f, obtained from an investigation using the Multhopp-Richardson program in ESDU 95010 (Derivation 29), provide values of $\bar{\eta}_{plan}$ for quarter-chord sweep angles of $\Lambda_{1/4} = 0, 10^\circ, 20^\circ, 30^\circ, 40^\circ$ and 45° , respectively for straight-tapered planform geometries. Values of $\bar{\eta}_{plan}$ at intermediate quarter-chord sweep angles may be obtained to a very good approximation using linear interpolation. Values of taper ratio, λ , and a reduced aspect ratio parameter, $A\sqrt{1-M^2}\cos^2\Lambda_{1/4}$, where A is wing aspect ratio and M is freestream Mach number, are used to obtain $\bar{\eta}_{plan}$ in Figures 6a to 6f.

When a spoiler extending across the starboard semi-span is deployed the resulting distribution of local lift coefficient increment on the starboard wing panel carries over onto part of the port wing panel. This causes the spanwise centre of pressure position due to the deployment of a semi-span spoiler to be further inboard than $\bar{\eta}_{plan}$. The correction factor, k_a , which is derived in Appendix A accounts for this effect and is obtained as a function of aspect ratio using Figure 3.

Values of $(C_{ls})_{ss}$ are obtained for $\alpha = 0$ and $\alpha = 10^\circ$ by using Equation (3.13) with values of ΔC_{LsF} obtained from Section 3.3.1.1. As for the ΔC_{LsF} characteristics, a linear variation of $(C_{ls})_{ss}$ with angle of attack is assumed, with limitations as outlined in Section 4.6.

* Geometric twist is the angle between a datum chord and the local chord at a given spanwise station. A wing with spanwise varying camber exhibits a form of twist known as aerodynamic twist.

3.3.2.2 Part-span factor for spoiler rolling moment, Ψ_{ps}

The part-span factor for spoiler rolling moment, Ψ_{ps} , allows for a part-span spoiler and is determined using

$$\Psi_{ps} = \Psi_{\eta_o} - \Psi_{\eta_i}, \quad (3.14)$$

where Ψ_{η_o} is the value of a part-span parameter for rolling moment, Ψ_{η} , with $\eta = \eta_o$ and Ψ_{η_i} is the value of Ψ_{η} with $\eta = \eta_i$. Values of Ψ_{η_i} and Ψ_{η_o} are obtained from Figures 5a and 5b at positions η_i and η_o . Figures 5a and 5b were constructed using wind-tunnel test data for flat-plate spoilers, see Section 5 of ESDU TM 172. These figures are applicable to both flat-plate and flap-type spoilers, see Section 4.

4. ACCURACY AND APPLICABILITY

The method applies to both straight-tapered and cranked wing planforms with or without a body and with trailing-edge flaps undeployed. Since the deployment of a spoiler results in an increment of lift, which is not influenced by twist, the method is applicable to both twisted and untwisted wings, see Section 3.1 of ESDU TM 172 (Derivation 33).

Test data obtained from Derivations 1 to 13, 15 to 19 and 30 are presented in Sketches 4.1 to 4.4. The database consists of both semi-span and full-span wings. Lift coefficient increment test data were taken for deployed spoilers on both semi-span and full-span wings. However, the C_{ls} database was limited to deployed spoilers on full-span wings. Only a full-span wing model can adequately account for the spanwise centre of pressure position due to the deployment of a spoiler on one semi-span, see Section 3.3.2.1. Test data were not available for spoilers deployed on both semi-spans of a full-span wing. All of the wind-tunnel models used in Derivations 1 to 13, 15 to 19 and 30 had a single spoiler deployed on either the port or starboard semi-span. The lift coefficient increment test data are therefore taken to be equal to $\Delta C_{Ls}/2$ and predicted values of $\Delta C_{Ls}/2$ are compared with test data in Sketches 4.1 and 4.3.

Sketches 4.1 and 4.2 compare $\Delta C_{Ls}/2$ and C_{ls} data, for flat-plate spoilers, predicted by the method of Section 3.3 with wind-tunnel test data. Tables 4.2 and 4.3 give details of the wind-tunnel models and test conditions for flat-plate spoilers on wing-alone and wing-body geometries respectively.

Sketches 4.3 and 4.4 compare $\Delta C_{Ls}/2$ and C_{ls} data, for flap-type spoilers, predicted by the method of Section 3.3 with wind-tunnel test data. Table 4.4 gives details of a wind-tunnel model with a flap-type spoiler on a cranked wing with a body. Tables 4.5 and 4.6 give details of straight-tapered wind-tunnel models and test conditions for flap-type spoilers on a wing-alone geometry and wing-body geometries respectively.

The majority of the $\Delta C_{Ls}/2$ test data in Sketches 4.1 and 4.3 are predicted to within ± 0.03 . Sketches 4.2 and 4.4 show that most of the C_{ls} test data are predicted to within ± 0.003 .

The variation of ΔC_{Ls} and C_{ls} with the deflection angle, δ_h , of a flap-type spoiler is generally non-linear. Sketches 4.5 and 4.6 present test data showing examples of the non-linear variations of $\Delta C_{Ls}/2$ and C_{ls} with δ_h respectively. In these sketches data predicted using the method of this Data Item are shown to compare favourably with the test data.

The limits of applicability of Reynolds number, Mach number, spoiler sweep angle, spoiler span, and porosity are discussed in Sections 4.1 to 4.5. Applicable limits of spoiler deployment height and wing angle of attack are given in Section 4.6. The ranges of applicability for various geometric and flow parameters are summarised in Section 4.7.