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Contribution of ventral fins to sideforce and yawing moment derivatives due to sideslip at low angle of attack



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CONTRIBUTION OF VENTRAL FINS TO SIDEFORCE AND YAWING MOMENT DERIVATIVES DUE TO SIDESLIP AT LOW ANGLE OF ATTACK

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CONTRIBUTION OF VENTRAL FINS TO SIDEFORCE AND YAWING MOMENT DERIVATIVES DUE TO SIDESLIP AT LOW ANGLE OF ATTACK

1. NOTATION AND UNITS (see Sketches 1.1 to 1.4)

The derivative notation used is that proposed in ARC R&M 3562 (Hopkin, 1970) and described in ESDU 86021. Coefficients and aeronormalised derivatives are evaluated in aerodynamic body axes, with origin at the aircraft centre of gravity and with the wing span as the characteristic length. The derivatives Y_v and N_v are often written as $\partial C_Y / \partial \beta$ and $\partial C_n / \partial \beta$ or $C_{Y\beta}$ and $C_{n\beta}$ in other systems of notation, but attention must be paid to the reference dimensions used and it is to be noted that a constant datum value of V is employed in the Hopkin system.

		SI	British
A_V	effective aspect ratio of ventral fin, $2h_V^2/S_V$		
a_{1F}	lift-curve slope for exposed main fin mounted on infinite reflection plane	rad ⁻¹	rad ⁻¹
a_{1V}	lift-curve slope for exposed ventral fin mounted on infinite reflection plane	rad ⁻¹	rad ⁻¹
b_T	tailplane span	m	ft
b_W	wing span	m	ft
c_{rF}	root chord of main fin, see ESDU 93007 ²⁵ , 91031 ²² and 82010 ¹⁹	m	ft
c_{rT}	root chord of tailplane	m	ft
c_{rV}	root chord of ventral fin, defined by intersection of fin half-chord line with body, see Sketches 1.1 and 1.2	m	ft
c_{rW}	root chord of wing	m	ft
c_{tF}	tip chord of main fin	m	ft
c_{tV}	tip chord of ventral fin	m	ft
$c_{0.4V}$	chord of ventral fin at 40% of exposed height, see Section 4	m	ft
h_{BF}	height of body cross-section at longitudinal station where main fin half-chord line meets body	m	ft
h_{BT}	height of body cross-section at longitudinal station where half-chord line of tailplane meets body	m	ft
h_{BV}	height of body cross-section at longitudinal station where half-chord line of ventral fin meets body	m	ft

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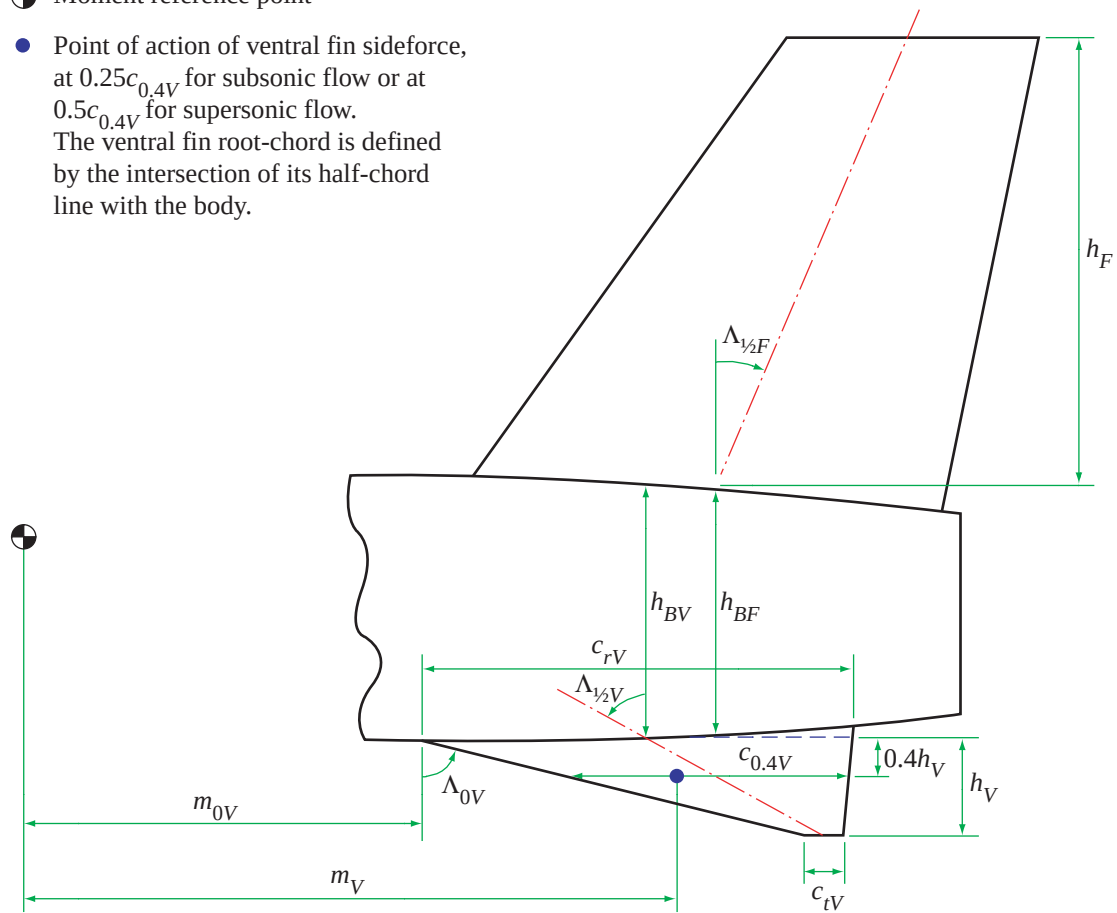
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h_{BW}	height of body cross-section at longitudinal station where half-chord line of wing meets body	m	ft
h_F	height of exposed main fin measured from fin tip to fin root chord defined by intersection of fin half-chord line with body	m	ft
h_V	height of exposed ventral fin, perpendicular distance from c_{rV} to fin tip, measured in plane of fin	m	ft
J_B, J_T	body and tailplane interference factors for main fin, see ESDU 82010 ¹⁹ and Section 7.3		
J_W	wing interference factor for main fin at subsonic speeds, ESDU 82010 ¹⁹ and 93007 ²⁵ and Sections 7.2 and 7.3.		
K_1, K_2	functions used in prediction of ventral fin interference factors		
K_F	overall interference factor for main fin		
K_V	overall interference factor for ventral fin		
$K_{V(B)}$	interference factor for ventral fin in presence of body		
$K_{V(BF)}$	interference factor for ventral fin in presence of body and main fin		
$K_{V(BFT)}$	interference factor for ventral fin in presence of body, main fin and tailplane		
$K_{V(BFW)}$	interference factor for ventral fin in presence of body, main fin and wing		
$K_{V(BT)}$	interference factor for ventral fin in presence of body and tailplane		
$K_{V(BW)}$	interference factor for ventral fin in presence of body and wing		
M_∞	free-stream Mach number		
m_F	longitudinal distance from moment reference point to point of action of sideforce increment due to main fin, see ESDU 91031 ²²	m	ft
m_V	longitudinal distance from moment reference point to point of action of sideforce increment due to ventral fin	m	ft
m_{0F}	longitudinal distance from moment reference point to leading edge of main fin root chord	m	ft
m_{0V}	longitudinal distance from moment reference point to leading edge of ventral fin root chord	m	ft
$\mathcal{N}$	yawing moment	N m	lbf ft

N_v	yawing moment derivative due to sideslip, $(\partial \mathcal{N} / \partial v) / (\frac{1}{2} \rho_\infty V_\infty S_W b_W)$		
ΔN_v	increment in N_v due to empennage		
$(\Delta N_v)_F$	increment in N_v due to main fin		
$(\Delta N_v)_T$	increment in N_v due to tailplane		
$(\Delta N_v)_V$	increment in N_v due to ventral fin		
S_F	exposed area of main fin	m ²	ft ²
S_V	exposed area of ventral fin	m ²	ft ²
$S_{V(B)}$	area of ventral fin influenced only by body	m ²	ft ²
$S_{V(BF)}$	area of ventral fin influenced by body and main fin	m ²	ft ²
$S_{V(BFT)}$	area of ventral fin influenced by body, main fin and tailplane	m ²	ft ²
$S_{V(BFW)}$	area of ventral fin influenced by body, main fin and wing	m ²	ft ²
$S_{V(BT)}$	area of ventral fin influenced by body and tailplane	m ²	ft ²
$S_{V(BW)}$	area of ventral fin influenced by body and wing	m ²	ft ²
S_W	wing (reference) area	m ²	ft ²
V_∞	free-stream velocity	m/s	ft/s
v	sideslip velocity	m/s	ft/s
w_{BF}	width of body cross-section at longitudinal station where half-chord line of main fin meets body	m	ft
w_{BT}	width of body cross-section at longitudinal station where half-chord line of tailplane meets body	m	ft
w_{BV}	width of body cross-section at longitudinal station where half-chord line of ventral fin meets body	m	ft
w_{BW}	width of body cross-section at longitudinal station where half-chord line of wing meets body	m	ft
Y	sideforce	N	lbf
Y_v	sideforce derivative due to sideslip, $(\partial Y / \partial v) / (\frac{1}{2} \rho_\infty V_\infty S_W)$		
ΔY_v	increment in Y_v due to empennage		

$(\Delta Y_v)_F$	increment in Y_v due to main fin		
$(\Delta Y_v)_V$	increment in Y_v due to ventral fin		
$(\Delta Y_v)_T$	increment in Y_v due to tailplane		
z_T	height of body-mounted tailplane above local body mid-point	m	ft
z_W	height of wing above local body mid-point	m	ft
α	angle of attack	deg	deg
β	angle of sideslip	deg	deg
Γ	ventral fin cant angle, see Sketch 1.4	deg	deg
Λ_{0V}	leading-edge sweep of ventral fin	deg	deg
$\Lambda_{1/2F}$	half-chord sweep of main fin	deg	deg
$\Lambda_{1/2T}$	half-chord sweep of tailplane	deg	deg
$\Lambda_{1/2V}$	half-chord sweep of ventral fin	deg	deg
$\Lambda_{1/2W}$	half-chord sweep of wing	deg	deg
λ_F	taper ratio of main fin, c_{tF}/c_{rF}		
λ_V	taper ratio of ventral fin, c_{tV}/c_{rV}		
μ	$\sin^{-1}(1/M_\infty)$ for $M_\infty \geq 1$	deg	deg
ρ_∞	free-stream density	kg/m ³	slug/ft ³

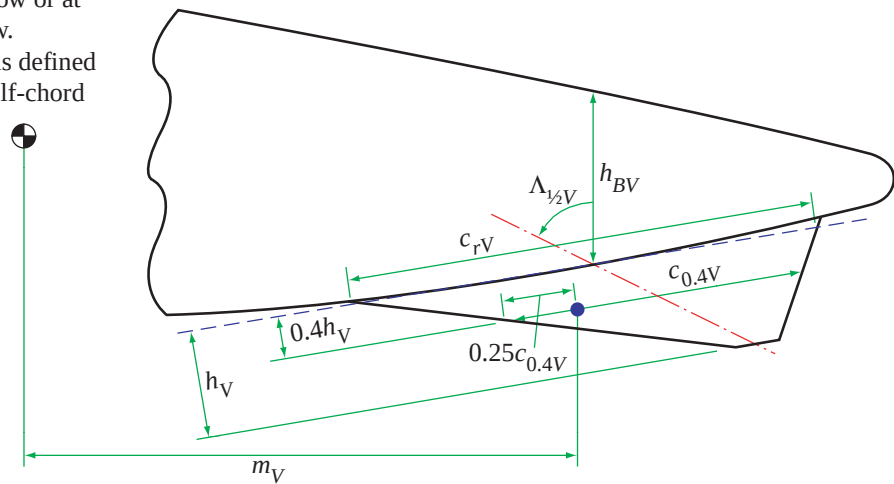
- ⊙ Moment reference point
- Point of action of ventral fin sideforce, at $0.25c_{0.4V}$ for subsonic flow or at $0.5c_{0.4V}$ for supersonic flow. The ventral fin root-chord is defined by the intersection of its half-chord line with the body.



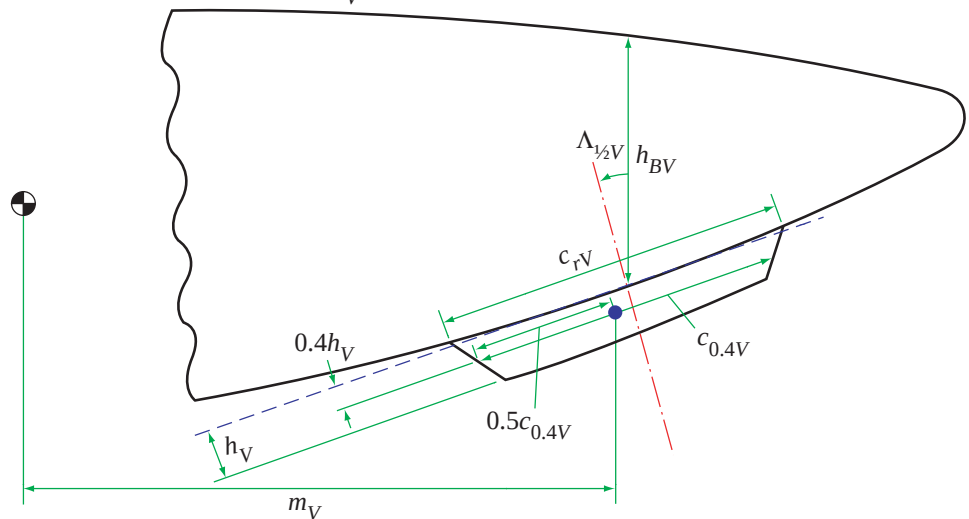
Sketch 1.1 Ventral fin geometry for body with little or no rear upsweep, ventral fin shown in plane of symmetry

- Point of action of ventral fin sideforce, at $0.25c_{0.4V}$ for subsonic flow or at $0.5c_{0.4V}$ for supersonic flow. The ventral fin root-chord is defined by the intersection of its half-chord line with the body.

(a) Subsonic flow

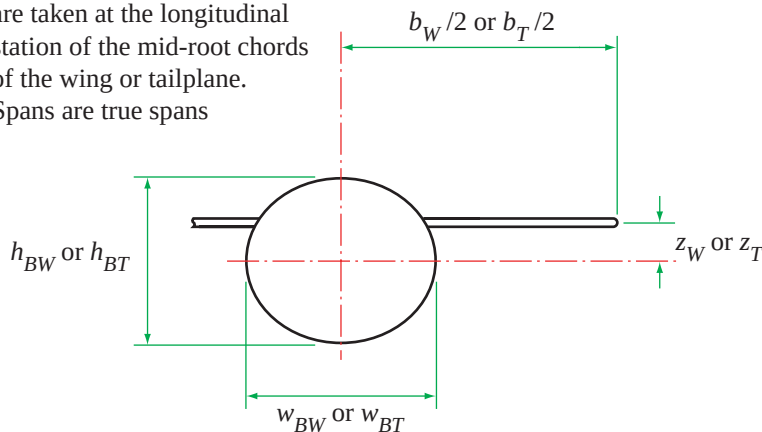


(b) Supersonic flow

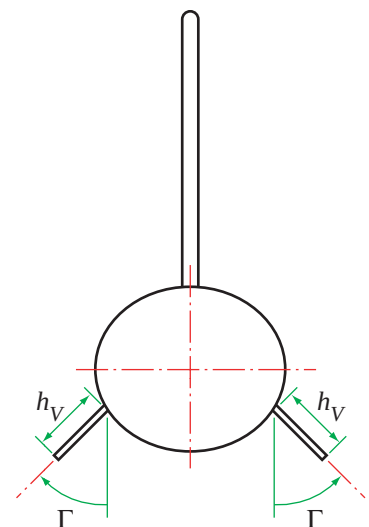


Sketch 1.2 Typical ventral fin geometries for bodies with rear upsweep, fin shown in plane of symmetry

Body heights and widths are taken at the longitudinal station of the mid-root chords of the wing or tailplane. Spans are true spans



Sketch 1.3 Wing or tailplane parameters



Sketch 1.4 Ventral fin angle

2. INTRODUCTION

This Item gives a method for estimating the contribution of ventral fins to the sideforce and yawing moment derivatives due to sideslip for an aircraft at low angles of attack ($\alpha < 5^\circ$) and of sideslip ($|\beta| \leq 4^\circ$). The basic method, described in Section 3, requires that any tailplane be mounted on the body and that the main fin be in the plane of symmetry. The ventral fin may be a single surface in the plane of symmetry or a pair of surfaces mounted outboard on the body and inclined at an angle Γ to the plane of symmetry.

The method is based on the techniques proposed in Derivation 11, with additional empirical modification. The ventral fin contribution is calculated via the application of interference factors that modify a basic lift-curve slope to allow for the presence of body, main fin, wing and tailplane. Those factors are based on the theoretical calculations made in Derivations 3 to 5. The basic lift-curve slope is calculated for the exposed ventral fin geometry mounted on an infinite reflection plane.

At supersonic speeds, proper allowance for interference effects requires an application of an interference factor appropriate to each of a number of separate zones on the ventral fin and these are defined by Mach lines from the leading and trailing edges of the root chords of the main fin, wing and tailplane.

The accuracy and applicability of the present method are addressed in Section 5, the Derivation is listed in Section 6, and separate worked examples for supersonic and subsonic speeds are given in Section 7.

The stability derivatives are given in aero-normalised form, see Derivation 21. Those of the empennage without ventral fins may be calculated by the methods of ESDU 93007 (Derivation 25) or ESDU 82010 (Derivation 19) for subsonic speeds or ESDU 91031 (Derivation 22) for supersonic speeds. The methods of ESDU 93007 and 91031 were also developed empirically from the theoretical calculations in Derivation 11 and are closely related to the present Item.

3. EFFECT OF VENTRAL FIN ON SIDEFORCE

The increment in the sideforce derivative due to a single ventral fin in the plane of symmetry is

$$(\Delta Y_v)_V = -a_{1V} K_V S_V / S_W \quad (3.1)$$

or for a pair of ventral fins at an angle Γ to the plane of symmetry

$$(\Delta Y_v)_V = -2a_{1V} K_V S_V (\cos^2 \Gamma) / S_W, \quad (3.2)$$

where the variation with $\cos^2 \Gamma$ is due to the decrease in the incidence of the fins and the resolution of the forces on them. See, for example, the theoretical and experimental results given for V-tails in Derivations 1 and 18, but note that the ventral fins are assumed to be small enough relative to the body to avoid significant interference between them.

Many ventral fins are of quite low aspect ratio and the lift-curve slope can be expected to be close to the slender-body-theory value $a_{1V} = 0.5\pi A_V$, with analysis of experimental data suggesting the empirical modifications

$$a_{1V} = 0.47\pi A_V \text{ for } M_\infty < 1, \text{ provided } (1 - M_\infty^2)^{1/2} A_V < 1.0 \text{ and } A_V \tan \Lambda_{1/2V} < 1.0 \quad (3.3a)$$

$$\text{and } a_{1V} = 0.54\pi A_V \text{ for } M_\infty > 1, \text{ provided } (M_\infty^2 - 1)^{1/2} A_V < 1.5 \text{ and } A_V \tan \Lambda_{1/2V} < 1.5. \quad (3.3b)$$

Outside of the qualifying ranges a_{1V} is obtained from ESDU 70011 (Derivation 14) at subsonic speeds and from ESDU 70012 (Derivation 15) at supersonic speeds as the lift-curve slope of a straight-tapered wing of aspect ratio $A_V = 2h_V^2/S_V$, taper ratio λ_V and half-chord sweep angle $\Lambda_{1/2V}$. For forward-swept fins $|\Lambda_{1/2V}|$ should be used in place of $\Lambda_{1/2V}$, see Derivations 6 and 20.

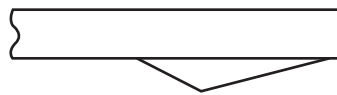
The evaluation of the interference factor K_V depends on the empennage geometry and the speed regime, see Sections 3.1 and 3.2.

3.1 Subsonic Speeds

The relative magnitude of the spans of the empennage panels and body diameters are used in the calculation of K_V . Strictly, the theoretical calculations require that the trailing edges of all the panels of the empennage be in the base plane of the body. However, the comparisons with experimental data made in Derivation 11 demonstrate that it is possible to relax this restriction and ignore small differences in the longitudinal locations of the tips of each panel. Body diameters can be sensibly defined at the longitudinal station of the mid-point of the root chord of the panel of interest. Interference from wing or tailplane will be present if the ventral fin lies below such surfaces. If the wing or tailplane extends over only part of the ventral fin or is just clear of it the user should study the effect of including and omitting wing or tailplane interference in order to establish a tolerance on the predicted sideslip derivatives.

Sketches 3.1(i) to 3.1(vi) illustrate different empennage configurations. At subsonic speeds K_V takes a single value $K_{V(B)}$, $K_{V(BF)}$ etc. according to which components have an interference effect on the ventral fin. So that for the six cases shown in the sketches,

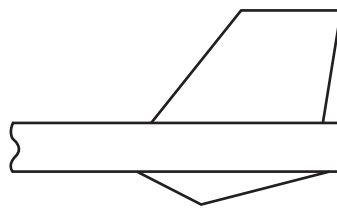
- (i) $K_V = K_{V(B)}$ as there is only interference from the body
- (ii) $K_V = K_{V(BF)}$ as there is only interference from the body and main fin
- (iii) $K_V = K_{V(BW)}$ as there is only interference from the body and wing
- (iv) $K_V = K_{V(BT)}$ as there is only interference from the body and tailplane
- (v) $K_V = K_{V(BFW)}$ as there is interference from the body, main fin and wing
- and (vi) $K_V = K_{V(BFT)}$ as there is interference from the body, main fin and tailplane.



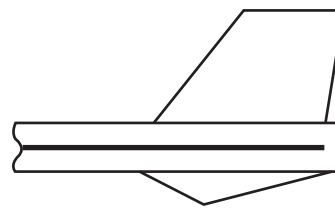
(i) $K_V = K_{V(B)}$



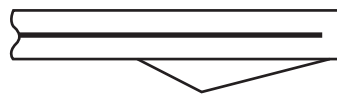
(iv) $K_V = K_{V(BT)}$



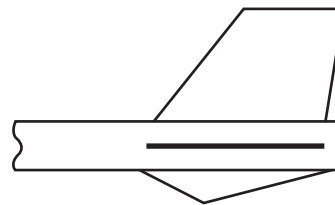
(ii) $K_V = K_{V(BF)}$



(v) $K_V = K_{V(BFW)}$



(iii) $K_V = K_{V(BW)}$



(vi) $K_V = K_{V(BFT)}$

Sketch 3.1 Interference factors for subsonic speeds

With the form of K_V identified, the relevant Figure(s) for its determination can be found from Table 3.1. Each of the Figures gives values of the functions K_1 and K_2 that are independent of ventral fin geometry. The value of K_V is then obtained as a function of the ratio of exposed ventral fin span to body height via the equation

$$K_V = K_1 + K_2 \left(\frac{1 - 2h_V/h_{BV}}{1 + 2h_V/h_{BV}} \right). \quad (3.4)$$

For example, in the case shown in Sketch 3.1(vi)

$$K_V = K_{V(BFT)} = K_1 + K_2 \left(\frac{1 - 2h_V/h_{BV}}{1 + 2h_V/h_{BV}} \right),$$

where K_1 and K_2 are determined from Figures 4a to 4i. See also the worked examples in Sections 7.2 and 7.3.

TABLE 3.1

Interference factor	K_1 and K_2 from Figure No.	w_{BW}/h_{BW} or w_{BT}/h_{BT}	$2z_W/h_{BW}$ or $2z_T/h_{BT}$	w_{BV}/h_{BV}	$h_{BF}/(h_F + h_{BF})$	w_{BW}/b_W or w_{BT}/b_T
$K_{V(B)}$	1	—	—	0.5 to 4	—	—
$K_{V(BF)}$	2	—	—	0.5 to 4	0.1 to 0.5	—
$K_{V(BW)}$	3a	0.5 to 4	0 mid-wing or tailplane	—	—	0.1 to 0.5
or	3b	1	−1 low wing or tailplane	—	—	0.1 to 0.5
$K_{V(BT)}$	3b	1	+1 high wing or tailplane	—	—	0.1 to 0.5
$K_{V(BFW)}$	4a	4	0 mid-wing or tailplane	—	0.1 to 0.5	0.1 to 0.5
	4b	3				
	4c	2				
	4d	1.5				
	4e	1				
or	4f	0.75	−1 low wing or tailplane	—	0.1 to 0.5	0.1 to 0.5
	4g	0.5				
$K_{V(BFT)}$	4h	1				
	4i	1	+1 high wing or tailplane	—	0.1 to 0.5	0.1 to 0.5

All the factors K_1 and K_2 were derived by taking advantage of the fact that to a good approximation K_V varies linearly with $h_{BV}/(h_{BV} + 2h_V)$ for practical values of that parameter between 0.5 and 1, and imposing a linear fit through the values of K_V at 0.6 and 0.9. Agreement between the linearised and true values of K_V is excellent for $w_{BV}/h_{BV} > 1$; it becomes slightly poorer as w_{BV}/h_{BV} decreases below unity but is still within $\pm 10\%$ for $w_{BV}/h_{BV} = 0.5$.

If the values of body width to height ratio and wing or tailplane height are intermediate to the values used in the various Figures a cross-plot is required, as shown in the worked examples of Section 7.

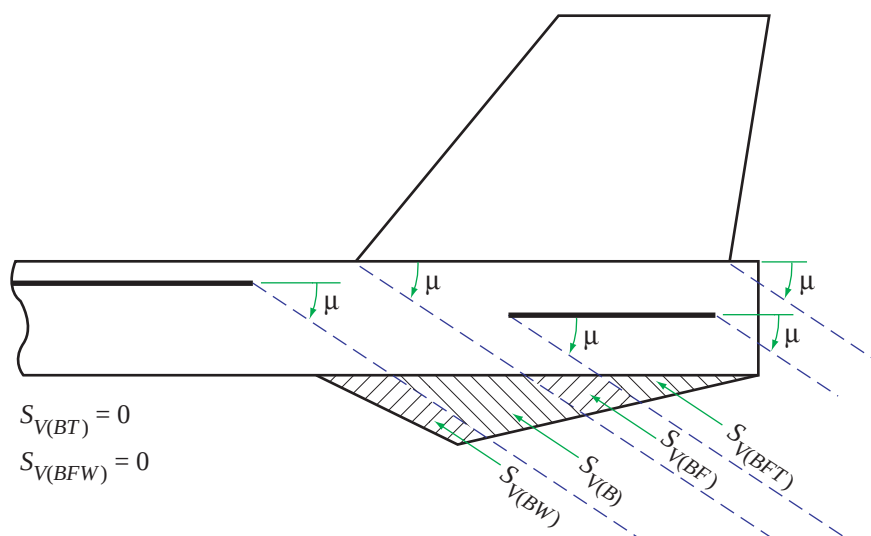
3.2 Supersonic Speeds

At supersonic speeds different interference factors are attributed to separate parts of the ventral fin and an area weighting is used to obtain a composite overall factor K_V . The parts affected by the wing, tailplane or main fin are determined by a planar projection onto the plane of the ventral fin of the Mach lines at angle $\mu = \sin^{-1}(1/M_\infty)$ emanating from the leading and trailing edges of the root chords of those components. It is assumed that the presence of wing, tailplane or main fin is experienced only within the boundaries so defined. Reference to Table 3.1 allows the Figures for the relevant interference factors to be chosen, and the overall factor is

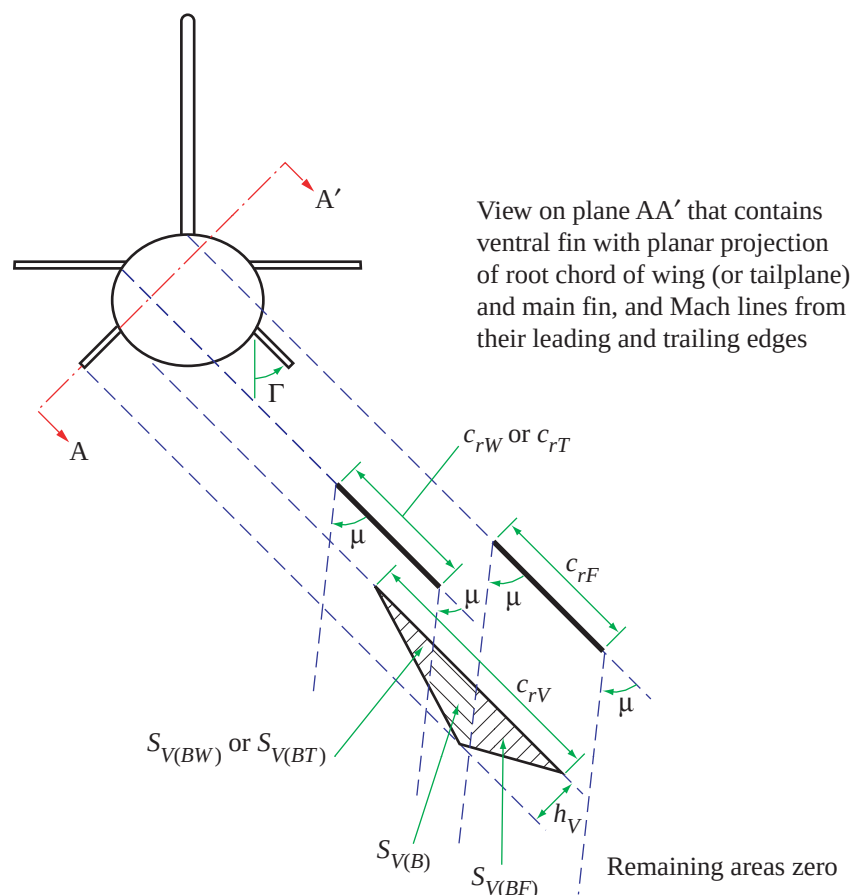
$$K_V = (K_{V(B)} S_{V(B)} + K_{V(BF)} S_{V(BF)} + K_{V(BW)} S_{V(BW)} + K_{V(BT)} S_{V(BT)} + K_{V(BFW)} S_{V(BFW)} + K_{V(BFT)} S_{V(BFT)}) / S_V \quad (3.5)$$

Sketch 3.2 gives an example of the way in which various interference areas appearing in Equation (3.5) are defined for a ventral fin that lies in the plane of symmetry. See also the worked example in Section 7.1.

Sketch 3.3 illustrates the calculation of interference areas for one of a pair of ventral fins at an angle Γ to the plane of symmetry. The areas are determined by the position of the root chord of the main fin and of the half-wing on the same side of the body as the ventral fin. The same areas apply for each ventral fin so only a single construction is necessary for each Mach number of interest.



Sketch 3.2 Example of zones of influence at supersonic speeds for ventral fin in plane of symmetry



Sketch 3.3 Example of zones of influence at supersonic speeds for ventral fin not in plane of symmetry

4. YAWING MOMENT DERIVATIVE

The yawing moment derivative due to the ventral fin is calculated by taking the point of action of the fin sideforce to be at $0.25c_{0.4V}$ for $M_\infty < 1$ and at $0.5c_{0.4V}$ for $M_\infty > 1$ where $c_{0.4V}$ is the ventral fin chord at a distance $0.4h_V$ from its root chord, measured in the plane of the fin.

$$\text{So that} \quad (\Delta N_v)_V = -(\Delta Y_v)_V \frac{m_V}{b_W} \quad (4.1)$$

For an aircraft with little or no rear-body upsweep in the vicinity of the ventral fin

$$m_V = m_{0V} + 0.4h_V \tan \Lambda_{0V} + 0.25c_{0.4V} \quad \text{for } M_\infty < 1 \quad (4.2)$$

$$\text{and} \quad m_V = m_{0V} + 0.4h_V \tan \Lambda_{0V} + 0.5c_{0.4V} \quad \text{for } M_\infty > 1, \quad (4.3)$$

where m_{0V} is the distance of the leading-edge of the ventral fin root chord aft of the moment reference point and Λ_{0V} is its leading-edge sweep, see Sketch 1.1.

If there is significant rear-body upsweep, geometric constructions such as those illustrated in Sketches 1.2a and 1.2b will give m_V directly.

5. ACCURACY AND APPLICABILITY

5.1 Accuracy

The accuracy of the method has been assessed by a comparison of predicted values with the experimental data contained in Derivations 2, 7 to 13, 16, 17, 23 and 24. Sketches 5.1a and 5.1b show predicted and experimental values of $(\Delta Y_v)_V(S_W/S_V)$ and $(\Delta N_v)_V(S_W/S_V)$ for configurations tested with ventral fins present and absent. For both those parameters, the scatter is generally contained within $\pm(0.15 + 15\%)$. Comparisons between the predicted and experimental values of the total effect of an empennage with a ventral fin have also been made and it has been found that the accuracy of prediction is as good as that for empennages with a single main fin predicted by the methods in ESDU 82010 and 93007 (± 0.08 on ΔY_v and ± 0.04 on ΔN_v) and 91031 ($\pm 15\%$ on ΔY_v and ΔN_v). The method of Derivation 11 was developed only for ventral fins in the plane of symmetry, but the extension made in this Item to cater for twin ventral fins has been found to give good predictions for the available experimental data.

5.2 Applicability

Table 5.1 gives the ranges of Mach number and geometric parameters covered in the experimental data base. Although the theoretical calculations for the Figures were performed for bodies of circular or elliptical cross-section, the height to width ratio is considered to be the only important body shape parameter in determining K_V and so the Figures can be employed for any practical body cross-section. For supersonic speeds, Section 5 of ESDU 91031 discusses the sensitivity of the definition of interference zones in relation to the predictions of the effect of a single main fin, and the same remarks are true for ventral fins.

TABLE 5.1

Parameter	Range	Parameter	Range
M_∞	$\leq 0.8, 1.5$ to 3.0	$h_{BF}/(h_F + h_{BF})$	0.22 to 0.45
m_V/b_W	0.3 to 0.6	Λ_{0V}	0 to 70°
w_{BV}/h_{BV}	0.9 to 2.6	λ_V	0 to 1
S_V/S_F	0.1 to 0.7	A_V	0.12 to 1.2
Γ	0 and 25°	h_V/h_{BV}	0.1 to 0.8

A comparatively simple approach has been adopted for the determination of the aerodynamic centre position of the ventral fin and this has proved satisfactory. During the development of the Item, the effect of using values based on the more precise theories of Derivations 6, 14, 15 and 20 was studied, but no significant improvement in the accuracy of prediction was gained. Their inclusion at the cost of greater complexity was therefore unwarranted.

There is some choice within the basic theoretical method as to where to define body widths and heights in practical cases. The ratio of body width to height will not usually change greatly in the region of the empennage, so the exact station chosen should not introduce significant error into the evaluation of K_V . The determination of the ratio of exposed span to body height is more likely to introduce some variation. The methods of ESDU 82010 and 93007 for predicting the effect of the main fin at subsonic speeds work with body heights and widths and an exposed main fin geometry that are defined by the intersection of the fin quarter-chord line with the body. The method in ESDU 91031 for the calculation of the main fin characteristics at supersonic speeds uses the intersection of the fin half-chord line and the body for definition purposes. In the present method the ventral fin characteristics are based on geometric parameters and an exposed planform that is defined by the intersection of the half-chord line and the body for all speeds. For