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Contribution of fin and tailplane to sideforce and yawing moment derivatives due to sideslip at supersonic speeds at low angle of attack

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CONTRIBUTION OF FIN AND TAILPLANE TO SIDEFORCE AND YAWING MOMENT DERIVATIVES DUE TO SIDESLIP AT SUPERSONIC SPEEDS AT LOW ANGLE OF ATTACK

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CONTRIBUTION OF FIN AND TAILPLANE TO SIDEFORCE AND YAWING MOMENT DERIVATIVES DUE TO SIDESLIP AT SUPERSONIC SPEEDS AT LOW ANGLE OF ATTACK

1. NOTATION AND UNITS

The derivative notation used is that proposed in ARC R&M 3562 (Hopkin, 1970) and described in Item No. 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_F	effective aspect ratio of fin, $2h_F^2/S_F$, see Section 3.2		
a_{1F}	lift-curve slope for exposed fin mounted on infinite reflection plane, see Section 3.2	rad^{-1}	rad^{-1}
b_T	tailplane span	m	ft
b_W	wing (reference) span	m	ft
$\bar{c}_F$	aerodynamic mean chord of fin	m	ft
c_{rF}	root chord of fin, see Sketch 1.1	m	ft
c_{rT}	root chord of tailplane	m	ft
c_{tF}	tip chord of fin	m	ft
h_{BF}	height of body cross-section at mid-root-chord station of fin	m	ft
h_{BT}	height of body cross-section at mid-root-chord station of tailplane	m	ft
h_{BW}	height of body cross-section at mid-root-chord station of wing	m	ft
h_F	height of exposed fin, see Sketch 1.1	m	ft
$K_{B(T)}$	interference factor for body in presence of tailplane		
$K_{B(T)max}$	value of $K_{B(T)}$ for tailplane mounted tangentially at top or bottom of cylindrical body		
K_F	overall interference factor for fin		

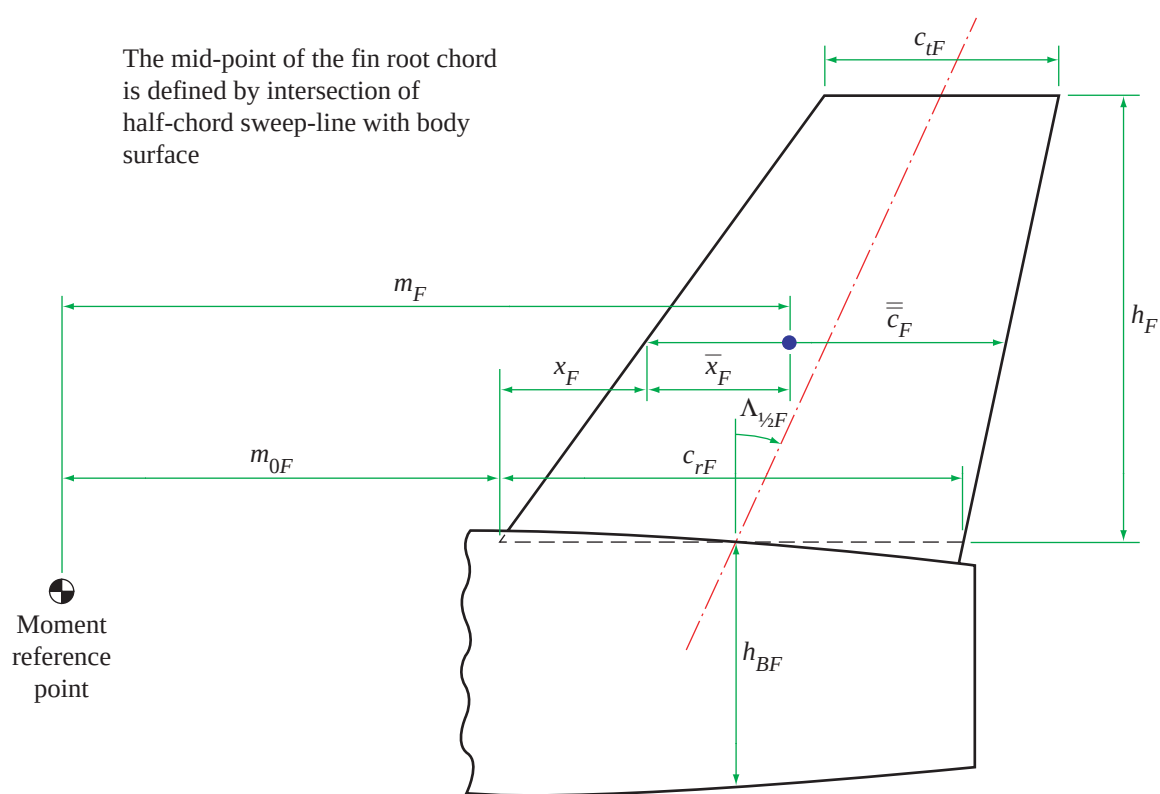
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$K_{F(B)}$	interference factor for fin in presence of body		
$K_{F(BT)}$	interference factor for fin in presence of body and tailplane		
$K_{F(BW)}$	interference factor for fin in presence of body and wing		
M_∞	free-stream Mach number		
m_F	longitudinal distance from moment reference point to point of action of sideforce increment due to fin	m	ft
m_{0F}	longitudinal distance from moment reference point to leading-edge of fin root chord, see Sketch 1.1	m	ft
m_T	longitudinal distance from moment reference point to centre of area $S_{B(T)}$	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 fin and tailplane		
$(\Delta N_v)_F$	increment in N_v due to fin		
$[(\Delta N_v)_F]_c$	part of $(\Delta N_v)_F / \eta_W$ due to cross-coupling effects between angles of attack and sideslip, see Equation (4.5)		
$[(\Delta N_v)_F]_I$	part of $(\Delta N_v)_F / \eta_W$ due to component interference, see Equation (4.5)		
$[(\Delta N_v)_F]_\Gamma$	part of $(\Delta N_v)_F / \eta_W$ due to forebody vortices, see Equation (4.5)		
$(\Delta N_v)_T$	increment in N_v due to tailplane		
$[(\Delta N_v)_T]_c$	part of $(\Delta N_v)_T$ due to cross-coupling effects between angles of attack and sideslip, see Equation (4.6)		
$[(\Delta N_v)_T]_I$	part of $(\Delta N_v)_T$ due to component interference, see Equation (4.6)		
$S_{B(T)}$	area of body influenced by tailplane	m ²	ft ²
S_F	area of fin	m ²	ft ²
$S_{F(B)}$	area of fin influenced only by body	m ²	ft ²
$S_{F(T)}$	area of fin influenced by tailplane	m ²	ft ²
$S_{F(W)}$	area of fin influenced by wing	m ²	ft ²

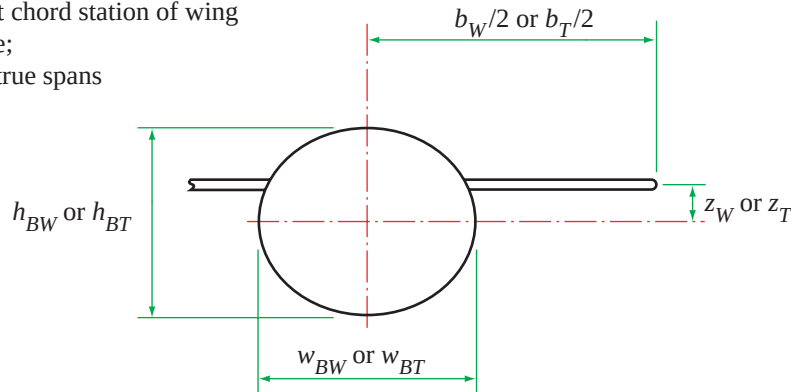
S_W	wing area	m ²	ft ²
V_∞	free-stream velocity	m/s	ft/s
v	sideslip velocity	m/s	ft/s
w_{BF}	width of body cross-section at mid-root-chord station of fin	m	ft
w_{BT}	width of body cross-section at mid-root-chord station of tailplane	m	ft
w_{BW}	width of body cross-section at mid-root-chord station of wing	m	ft
x_F	distance of leading edge of fin aerodynamic mean chord aft of leading edge of fin root chord	m	ft
$\bar{x}_F$	distance of position of aerodynamic centre of fin aft of leading edge of aerodynamic mean chord of fin	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 fin and tailplane		
$(Y_v)_B$	body-alone sideforce derivative		
$(\Delta Y_v)_F$	increment in Y_v due to fin		
$[(\Delta Y_v)_F]_c$	part of $(\Delta Y_v)_F/\eta_w$ due to cross-coupling effects between angles of attack and sideslip, see Equation (4.2)		
$[(\Delta Y_v)_F]_I$	part of $(\Delta Y_v)_F/\eta_w$ due to component interference, see Equation (4.2)		
$[(\Delta Y_v)_F]_\Gamma$	part of $(\Delta Y_v)_F/\eta_w$ due to forebody vortices, see Equation (4.2)		
$(\Delta Y_v)_T$	increment in Y_v due to tailplane		
$[(\Delta Y_v)_T]_c$	part of $(\Delta Y_v)_T$ due to cross-coupling effect between angles of attack and sideslip, see Equation (4.3)		
$[(\Delta Y_v)_T]_I$	part of $(\Delta Y_v)_T$ due to component interference, see Equation (4.3)		
z_T	height of tailplane above local body mid-point, see Sketch 1.2	m	ft
z_W	height of wing above local body mid-point, see Sketch 1.2	m	ft
α	angle of attack	deg	deg

β	angle of sideslip	deg	deg
η_B	compressibility parameter on body-alone sideforce derivative		
η_W	effectiveness parameter to account for wing flow field		
$\Lambda_{1/2F}$	half-chord sweep of fin	deg	deg
$\Lambda_{1/2T}$	half-chord sweep of tailplane	deg	deg
$\Lambda_{1/2W}$	half-chord sweep of wing	deg	deg
λ_F	taper ratio of fin, c_{tF}/c_{rF}		
ρ_∞	free-stream density	kg/m ³	slug/ft ³
μ	$\sin^{-1}(1/M_\infty)$	deg	deg



Sketch 1.1 Fin geometry

Body heights and widths are taken at mid-root chord station of wing or tailplane;
Spans are true spans



Sketch 1.2 Wing or tailplane parameters

2. INTRODUCTION

This Item gives a method for predicting the contribution of fin and tailplane to the sideforce and yawing moment derivatives due to sideslip for an aircraft at supersonic speeds at low angles of attack ($\alpha < 5^\circ$) and sideslip ($|\beta| \leq 4^\circ$). The basic method, described in Section 3, requires that any tailplane be mounted on the body and that the fin be in the plane of symmetry. A tailplane mounted on the fin has only a minor effect on sideforce and yawing moment and only a small change in the calculation procedure is required, see Section 3.5.

As angle of attack increases to moderate values there are substantial changes in sideforce and yawing moment due to a number of causes. Some indication of the relative importance of these effects is given in Section 4.

The method is based on the techniques proposed in Derivation 18, with additional empirical modification. The fin contribution is calculated via the application of interference factors that modify a basic fin lift-curve slope to allow for the presence of body, wing and tailplane. Those factors are based on the theoretical (apparent mass) calculations made in References 24, 25 and 26. The basic lift-curve slope is calculated for the exposed fin geometry mounted on an infinite reflection plane.

Proper allowance for interference effects requires an application of different interference factors to separate zones on the fin and these are defined by Mach lines and shock waves from the wing and tailplane. In addition to its interference effect on the fin, the tailplane contributes to the sideslip derivatives through interaction with the body.

The accuracy and applicability of the method are addressed in Section 5, the Derivation and References are listed in Section 6, and a worked example is given in Section 7. Appendix A extends the method to twin-fin configurations.

The derivatives are given in aero-normalised form, see Reference 30.

For the effect of ventral fins, see Item No. 92029 (Reference 31).

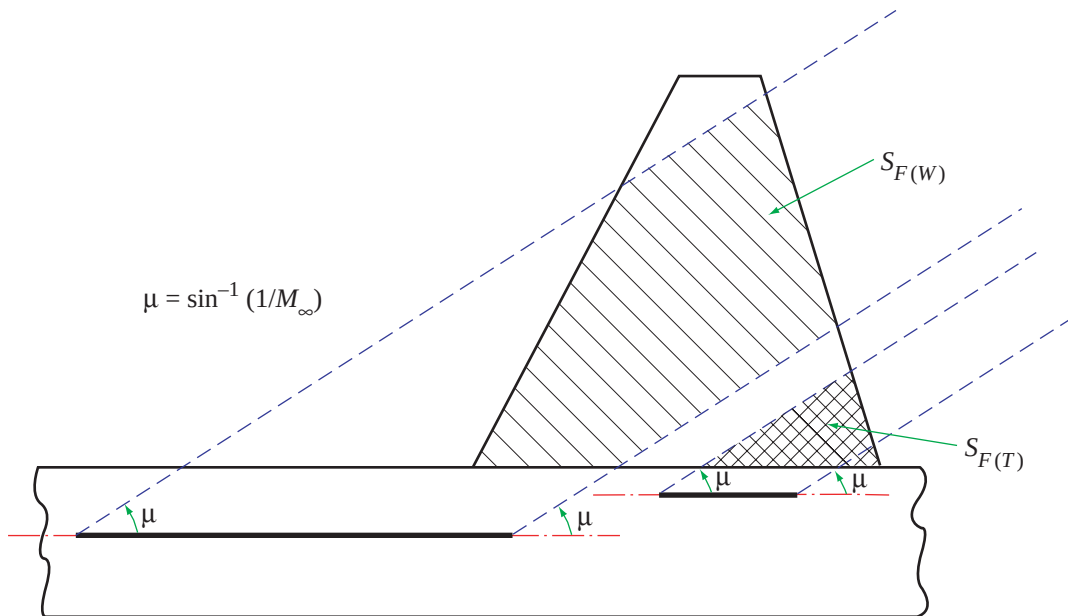
3. METHOD

3.1 Zones of Influence

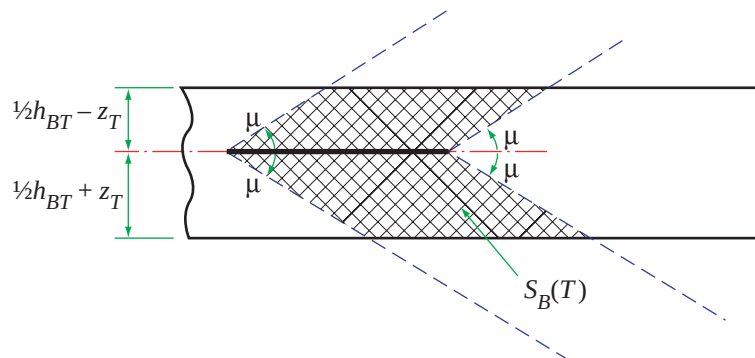
The zones affected by wing and tailplane are determined by a planar projection onto the plane of symmetry of the Mach lines and shock waves emanating from the leading and trailing edges of their root chords. It is assumed that the presence of the wing or tailplane is experienced only within the boundaries so defined. If the wing and tailplane are of thin section, at zero angle of attack the Mach lines at angle $\mu = \sin^{-1} (1/M_\infty)$ are used to define the zones of influence. This definition will be adequate for $\alpha < 5^\circ$.

Sketch 3.1a illustrates the definition of the areas of the fin influenced by the wing and tailplane, $S_{F(W)}$ and $S_{F(T)}$. These areas obviously depend on configuration geometry and vary as M_∞ changes; they may encompass the whole fin, only part of the fin, or they may be zero.

Sketch 3.1b illustrates the definition of the area of the body influenced by the tailplane, $S_{B(T)}$. See also Section 3.3.



Sketch 3.1a Fin areas $S_{F(W)}$ and $S_{F(T)}$



Sketch 3.1b Body areas $S_{B(T)}$

3.2 Effect of Fin on Sideforce

The increment to the sideforce derivative due to the fin is

$$(\Delta Y_v)_F = -a_{1F} K_F S_F / S_W \quad (3.1)$$

where
$$K_F = [K_{F(B)} S_{F(B)} + K_{F(BW)} S_{F(W)} + K_{F(BT)} S_{F(T)}] / S_F. \quad (3.2)$$

The zones of influence $S_{F(W)}$ and $S_{F(T)}$ are determined as described in Section 3.1. The area of the fin is S_F and so the area affected only by the body is

$$S_{F(B)} = S_F - S_{F(W)} - S_{F(T)}. \quad (3.3)$$

The basic lift-curve slope a_{1F} is taken as that for the exposed fin geometry mounted on an infinite reflection plane, and is obtained from Item No. 70012 (Reference 28) as the lift-curve slope of a straight-tapered wing of aspect ratio $A_F = 2h_F^2/S_F$, taper ratio λ_F and half-chord sweep angle $\Lambda_{1/2F}$.

The factor $K_{F(B)}$ is given in Figure 1 and is taken directly from Derivation 18.

The factors $K_{F(BW)}$ and $K_{F(BT)}$ are given in Figures 2a to 2g for a body of circular or elliptical cross-section with wing or tailplane at mid-height on the body, and in Figures 2h and 2i for a body of circular cross-section with wing or tailplane in low or high position on the body, see Table 3.1.

The factors for a high wing or tailplane have been taken directly from Derivation 18. As the height of the wing or tailplane decreases the theoretical interference factors increase, but comparisons with experimental data show that the theoretical rate of increase is too fast, and so an empirical reduction to counteract this has been made in the factors given for a wing or tailplane at mid-position or low position.

Although the data in the Figures are for circular or elliptical cross-sections, the height to width ratio of the body is considered to be the important parameter. The Figures can therefore be employed for any practical cross-section shape.

For a body of general height to width ratio, with wing or tailplane at a general height, cross-plots must be made between the cases summarised in Table 3.1 (see Example, Section 7).

TABLE 3.1 Interference Factors of Body-wing or Body-tailplane on Fin

<i>Body cross-section width to height ratio</i>	<i>Height on body of wing or tailplane</i>	<i>Figure for</i>
w_{BW}/h_{BW} or w_{BT}/h_{BT}	$2z_W/h_{BW}$ or $2z_T/h_{BT}$	$K_{F(BW)}$ or $K_{F(BT)}$
4	0	2a
3	0	2b
2	0	2c
1.5	0	2d
1	0	2e
0.75	0	2f
0.5	0	2g
1	-1 (low)	2h
1	1 (high)	2i

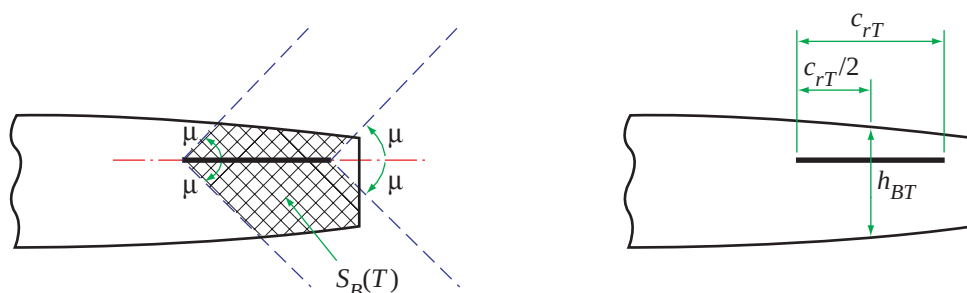
3.3 Effect of Body-mounted Tailplane on Sideforce

If the body-alone sideforce derivative is $(Y_v)_B$ (based on S_W as reference area) then the incremental effect of adding a tailplane to an infinite cylindrical body with zone of influence as defined in Sketch 3.1b is obtained by application of the theoretical factor $K_{B(T)}$, so that

$$(\Delta Y_v)_T = K_{B(T)}(Y_v)_B \quad (3.4)$$

For a tapered afterbody the area $S_{B(T)}$, is calculated as shown in Sketch 3.2, and the value of $(\Delta Y_v)_T$ is adjusted by the ratio of the area actually affected to the theoretical area for an infinite cylinder of diameter h_{BT} , so that

$$(\Delta Y_v)_T = K_{B(T)}(Y_v)_B S_{B(T)} / (c_{rT} h_{BT}) \quad (3.5)$$



Sketch 3.2 Body area $S_{B(T)}$ for tapered afterbody

The factor $K_{B(T)}$ is obtained from the formula

$$K_{B(T)} = K_{B(T)max} \left\{ 1 - \left[1 - \left(\frac{2z_T}{h_{BT}} \right)^2 \right]^{1/2} \right\} \quad (3.6)$$

where $K_{B(T)max}$ is given in Figure 3 and is the value of $K_{B(T)}$ for a tailplane mounted tangentially at the top or bottom of the body. Equation (3.6) gives a variation between those values and the value of zero for a tailplane in mid-position.

The value of $(Y_v)_B$ may be approximated by

$$(Y_v)_B = - \left(\frac{\pi}{2} \right) w_{BT} h_{BT} \eta_B / S_W \quad (3.7)$$

where the slender-body theory value has been modified by the compressibility correction factor η_B introduced in Derivation 19 and reproduced in Figure 4.

3.4 Yawing Moment Derivatives

The increment in yawing moment derivative due to a fin and a body-mounted tailplane is

$$\Delta N_v = -(\Delta Y_v)_F (m_F/b_W) - (\Delta Y_v)_T (m_T/b_W) \quad (3.8)$$

where m_F is the distance from the moment reference point to the point of action of the sideforce contribution due to adding the fin. If it is assumed that all of that contribution acts at the aerodynamic centre of the exposed fin geometry mounted on an infinite reflection plane, m_F can be written

$$m_F = m_{0F} + c_{rF} \left[\frac{x_F}{c_{rF}} + \left(\frac{\bar{x}_F}{\bar{c}_F} \right) \left(\frac{\bar{c}_F}{c_{rF}} \right) \right] \quad (3.9)$$

where

$$\frac{x_F}{c_{rF}} = \frac{(1 + 2\lambda_F)}{12} \left[A_F \tan \Lambda_{1/2F} + 2 \left(\frac{1 - \lambda_F}{1 + \lambda_F} \right) \right], \quad (3.10)$$

and $\bar{x}_F/\bar{c}_F$ may be found from Item No. 70012 for a straight-tapered wing of aspect ratio $A_F = 2h_F^2/S_F$, taper ratio λ_F and half-chord sweep angle $\Lambda_{1/2F}$.

For the tailplane contribution to the yawing moment derivative, m_T is the distance from the moment reference point to the centre of the area $S_{B(T)}$.

3.5 Fin-mounted Tailplanes

Available experimental results show that there is little contribution to sideforce and yawing moment due to a tailplane mounted on a fin, even for those at the fin tip. Therefore, it is recommended that estimates of the sideforce derivative be made as for a wing-body-fin configuration (with no tailplane). To estimate the yawing moment derivative it is assumed that tailplanes are mounted on the lower half of the exposed fin or close to the fin tip. For the former group, instead of Equation (3.9), the moment arm to be associated with the sideforce derivative is measured longitudinally to the mid-point of the fin aerodynamic mean chord, while for the latter group the moment arm is measured longitudinally to the mid-chord at mid-span of the exposed fin. See also Section 5.

4. ANGLE OF ATTACK EFFECTS

The extension of the method of Derivation 18 that is made in Derivation 19 allows the sideforce derivative due to fin and tailplane at moderate angles of attack to be written

$$\Delta Y_v = (\Delta Y_v)_F + (\Delta Y_v)_T, \quad (4.1)$$

where $(\Delta Y_v)_F = \{[(\Delta Y_v)_F]_I + [(\Delta Y_v)_F]_C + [(\Delta Y_v)_F]_\Gamma\} \eta_W$ (4.2)

and $(\Delta Y_v)_T = [(\Delta Y_v)_T]_I + [(\Delta Y_v)_T]_C$. (4.3)

Similarly, the yawing moment derivative can be written

$$\Delta N_v = (\Delta N_v)_F + (\Delta N_v)_T, \quad (4.4)$$

$$(\Delta N_v)_F = \{[(\Delta N_v)_F]_I + [(\Delta N_v)_F]_C + [(\Delta N_v)_F]_\Gamma\} \eta_W \quad (4.5)$$

$$(\Delta N_v)_T = [(\Delta N_v)_T]_I + [(\Delta N_v)_T]_C. \quad (4.6)$$

These equations show the several additional effects that appear as angle of attack increases from zero.

The terms identified by $[]_I$ denote the contribution from interference between the body, wing, tailplane and fin and are dealt with in Section 3 for $\alpha = 0$. At angle of attack the same calculation techniques are applied, but the zones of influence can no longer be defined simply in terms of the Mach angle μ , and must be adjusted to correspond to the shock wave pattern appropriate to the angle of attack. There is also an additional angle of attack dependence in the tailplane contribution.

The terms identified by $[]_C$ denote the contributions from cross-coupling of angle of attack and sideslip. As shown experimentally and theoretically in Reference 27 there is a loss of force on the fin in the presence of the body due to the interaction of cross-flows; in addition there is a reduction in body cross-flow drag in the vicinity of the tailplane root chord. Both effects result in a small reduction in the magnitude of ΔY_v .

The terms identified by $[]_\Gamma$ denote the contributions due to interaction of the body vortices with the fin. As α increases the effect is to generate a growing positive sideforce. Accurate prediction depends on a knowledge of the vortex pattern near the fin.

The final effect at angle of attack is modelled through the factor η_W that allows for the reduction of fin effectiveness due to changes of local dynamic pressure and Mach number in the wing flow field. The factor is taken as unity at $\alpha = 0$.

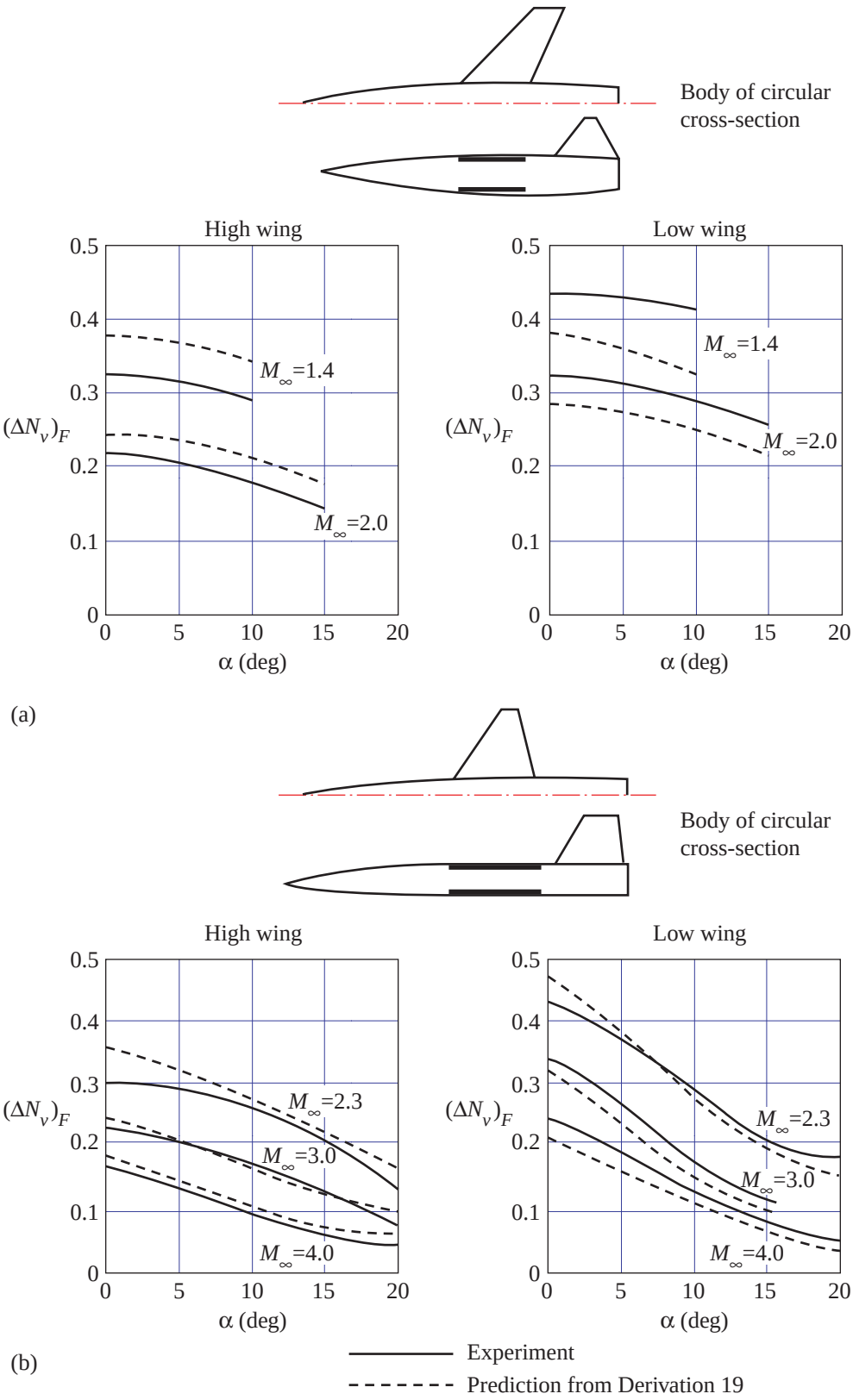
4.1 Examples of Variations with Angle of Attack

Some examples from Derivation 19 of predicted and experimental values of $(\Delta N_v)_F$ are given in Sketches 4.1a and 4.1b for wing-body-fin configurations, the bodies having circular cross-sections. It can be seen that the model set up in Equation (4.5) is quite successful in predicting the variation of experimental values in those cases.

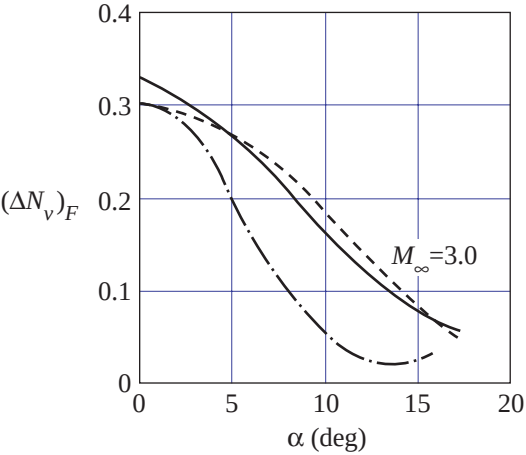
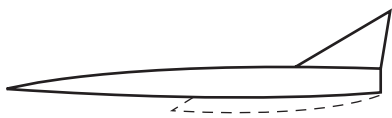
Comparison of the experimental data for low and high wings confirms that when there is wing-fin interference low wings have a beneficial effect and increase $(\Delta N_v)_F$, at low angles of attack. However, as the angle of attack increases the fin of a low-wing configuration more rapidly experiences adverse effects of the wing flow field and so $(\Delta N_v)_F$ decreases in magnitude more rapidly than for a high-wing configuration, and this becomes more noticeable at the higher Mach numbers.

One major difficulty in prediction arises from the vortex interference terms because of uncertainties in the estimation of vortex paths. The method of Derivation 19 is adequate for simple circular bodies, but its accuracy is difficult to assess for more complex practical geometries. For example, Sketch 4.2 contrasts predicted values for a body-fin configuration in the cases where the body has a circular cross-section along its whole length and where the cross-section is rectangular aft of the forebody. The different vortex patterns result in very different sideslip characteristics.

Sketch 4.3 gives an example of theoretical estimates of the various components in Equations (4.5) and (4.6) and the total ΔN_v for a combat aircraft; the most significant effect of angle of attack is found in $[(\Delta N_v)_F]_\Gamma$. Some *ad hoc* assumptions had to be made in the calculation of the body vortex contributions and a band of values is shown. The lower values of $[(\Delta N_v)_F]_\Gamma$ are those predicted by the standard method of Derivation 19 for a body of circular cross-section, while to investigate the alleviation that might be achieved by body shaping or body strakes (see Reference 29) the calculation has been made with vortex heights reduced by half and lateral spacing doubled. However, these values must only be treated as a simple indication of trends and relative magnitudes because actual values will depend greatly on the particular geometry of the aircraft being considered.

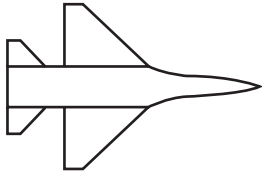
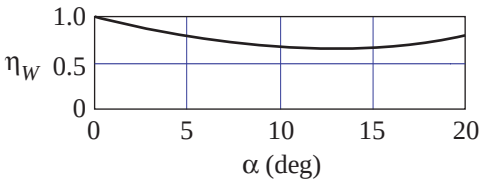
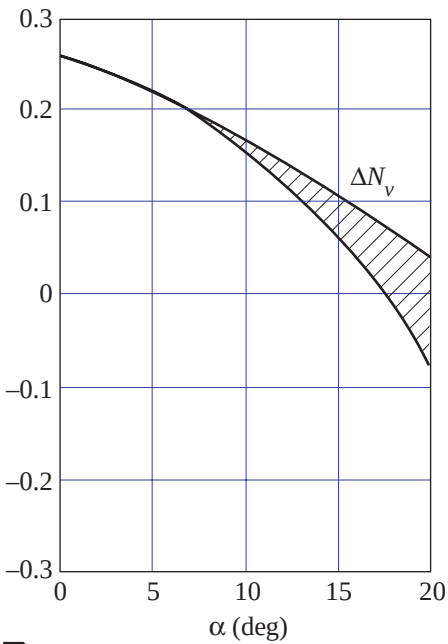
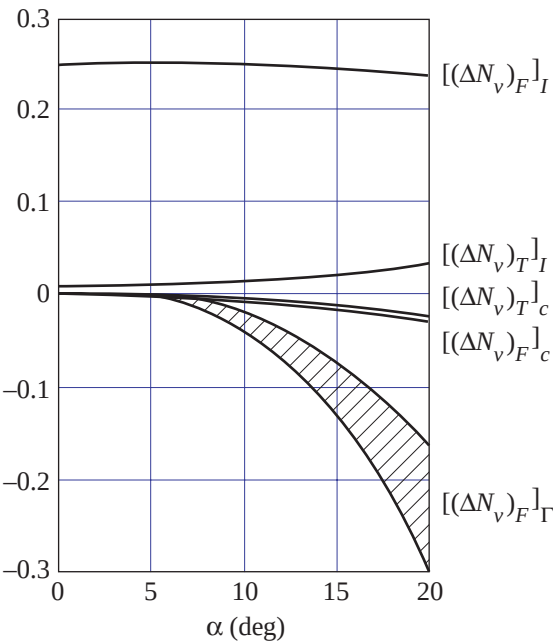


Sketch 4.1 Wing-body-fin configurations



- Experiment for body of circular cross-section
- · - Experiment for body of rectangular cross-section
- - - Prediction from derivation 19

Sketch 4.2 Effect of body cross-section



$M_\infty = 1.8$



Sketch 4.3 Predicted components of ΔN_v for combat aircraft

5. ACCURACY AND APPLICABILITY

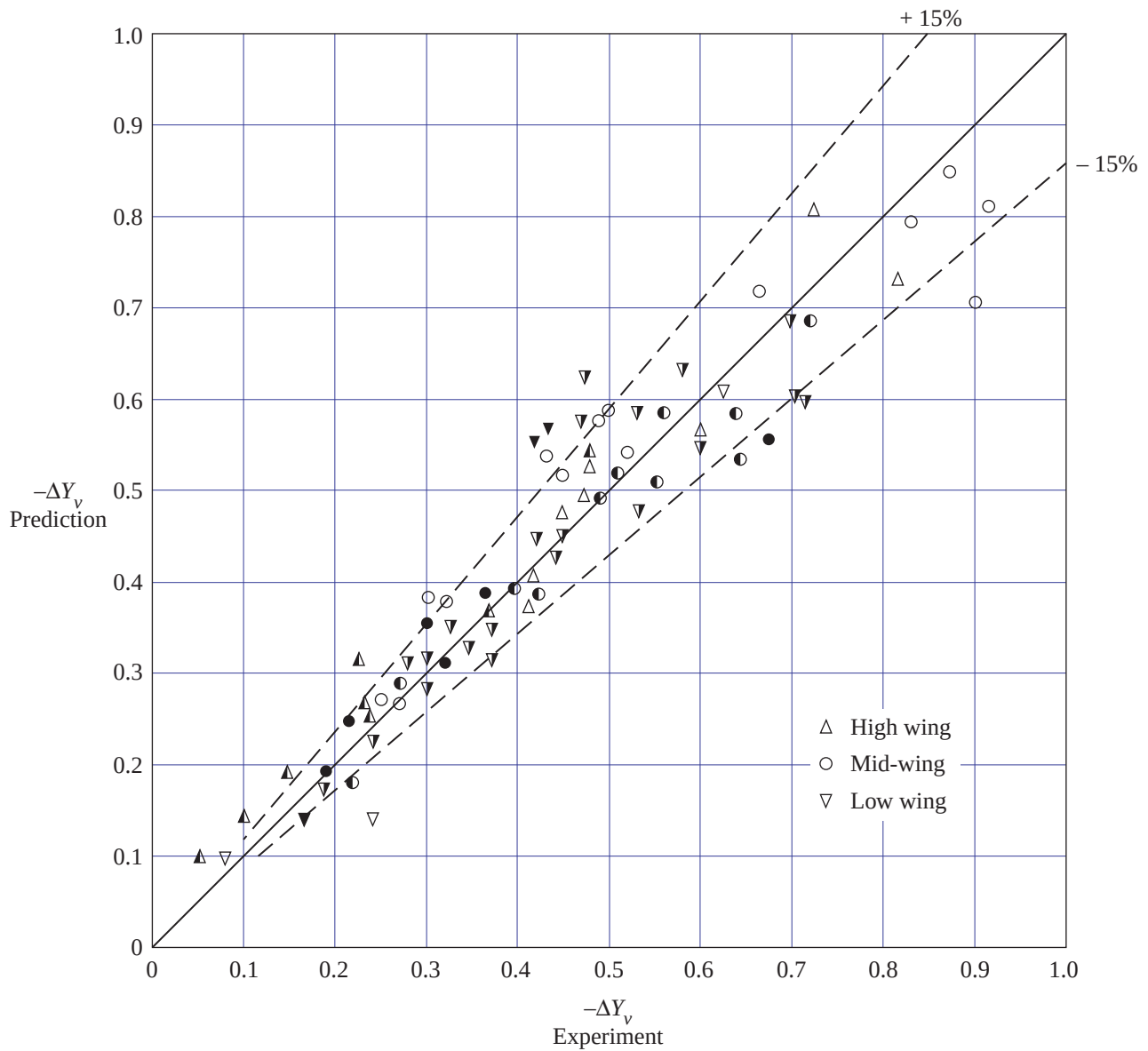
The method for low angle of attack has been tested through comparisons with experimental data contained in Derivations 1 to 22. This data base is more extensive than that of Derivation 18. As angle of attack rises stability derivatives are known to depart increasingly from their values at $\alpha = 0$ (see Sketches 4.1a and 4.1b, for example) and so the method, which is formally for zero angle of attack, can only be expected to apply with reasonable accuracy for $\alpha < 5^\circ$. The stability derivatives were all defined by the rate of change of sideforce and yawing moment coefficient with sideslip angle over a small interval about zero, typically $|\beta| \leq 4^\circ$. Most data were within the Mach number range $1.4 \leq M_\infty \leq 4$, with a few additional results extending the range to $1.1 \leq M_\infty \leq 5$. In assessing the accuracy it should be recognised that the lift-curve slope a_{1F} is predicted via Item No. 70012 which quotes a tolerance of $\pm 15\%$.

Sketch 5.1 shows the experimental and predicted values of ΔY_v and Sketch 5.2 compares values of ΔN_v . The accuracies are about $\pm 15\%$. To test the use of the aerodynamic centre of the exposed fin as the point of action of the increment in sideforce, experimental values of $\Delta N_v / (-\Delta Y_v)$ were examined. This indicated that the assumption was adequate, as is suggested by the fact that the overall accuracy in the prediction of ΔN_v is no worse than that of ΔY_v . It may also be noted that application of the theoretical methods available for symmetrical fin-body configurations in Reference 23 shows that, provided there is no afterbody, the body carry-over lift has little effect on the moment arm of the fin-body sideforce.

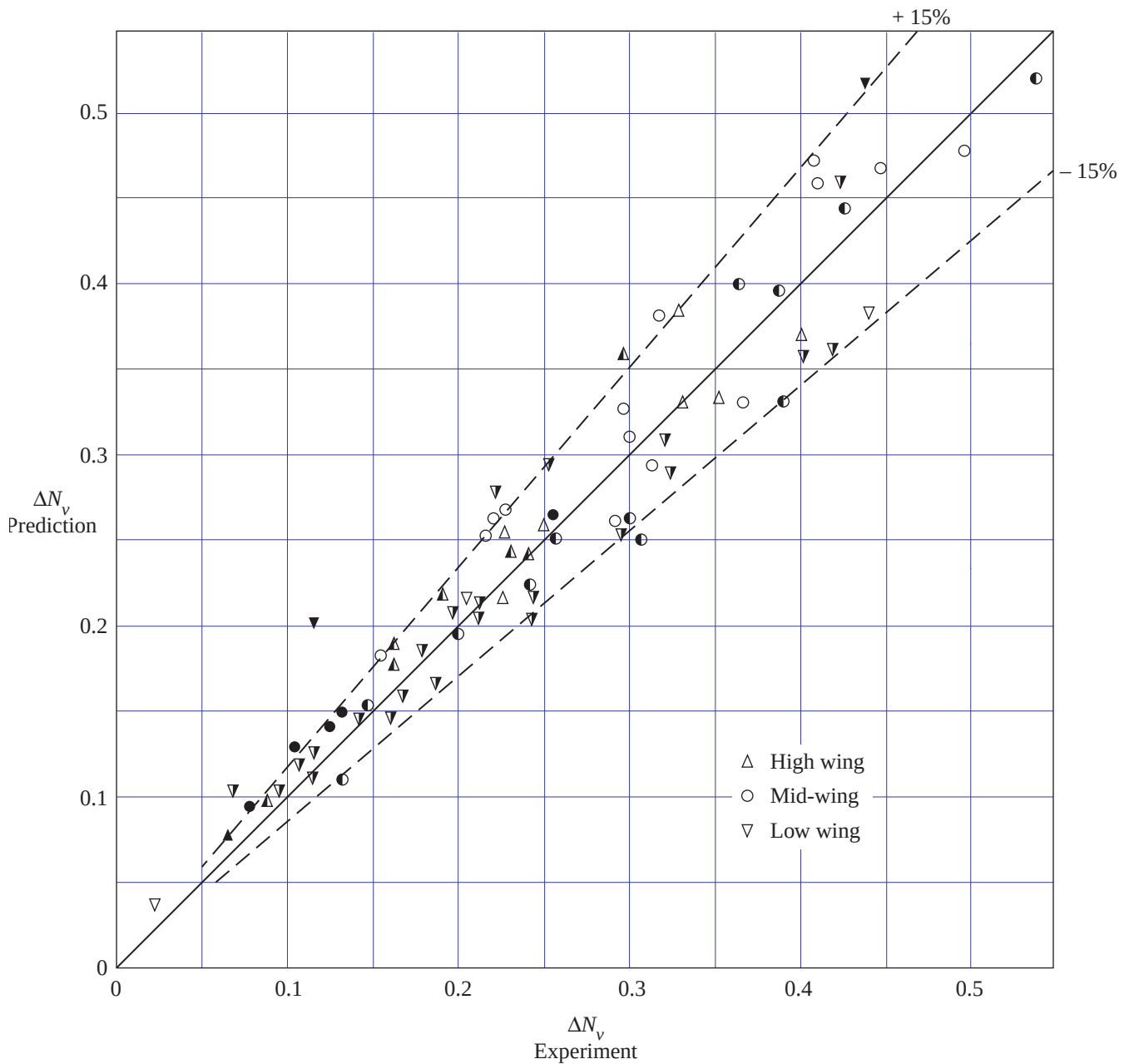
To define the exposed fin geometry, the fin root chord is drawn through the intersection of the half-chord sweep line and the body. For the data studied, the body height varied so little in the vicinity of the root chord that only minimal variations in predicted values would have been produced by the adoption of other techniques.

The definition of the zones of influence of the wing and tailplane on the fin is based on simple considerations that yield a well-defined geometric construction. In practice, the influence of the wing and tailplane will be experienced in less well-defined patterns, and fins that are theoretically just free from interference may in fact be influenced although they are downstream of the geometric Mach line drawn from the trailing edge of the root chord of the wing or tailplane. Sketch 5.3 gives an example taken from Derivation 19; theoretically the low wing does not affect the fin, but in practice there is a beneficial interference compared with the high-wing configuration. In the assessment of the method, consideration was given to a rearward shift in the zones of influence to allow for the size of the body cross-section and the delay it might cause in the fin experiencing interference effects. In some cases predictions were improved, as shown in Sketch 5.3, but in others they were worsened, which probably reflects to some degree the uncertainties that may be present when there is partial interference on a fin. Sketches 5.1 and 5.2 identify cases of full, partial or zero interference and show that they are distributed evenly within the general scatter. For this reason no changes were made to the procedures recommended in Derivation 19 but Sketch 5.3 can be taken as a warning on the sensitivity of the calculation when there is partial interference.

Sketch 5.4 compares predicted and experimental values of ΔN_v for configurations with fin-mounted tailplanes. The predictions were formed as recommended in Section 3.5. The agreement is generally comparable to that shown in Sketch 5.2 with only a slight tendency towards underestimates for configurations with tailplanes at the fin tip.



Sketch 5.1 Comparison of predicted and experimental values of ΔY_v



Open symbols: No wing or tailplane interference
 Half-open symbols: Partial wing or tailplane interference
 Closed symbols: Complete wing or tailplane interference

Sketch 5.2 Comparison of predicted and experimental values of ΔN_v