AERODYNAMIC CENTRE OF WING-FUSELAGE-NACELLE COMBINATIONS: EFFECT OF REAR-FUSELAGE PYLON-MOUNTED NACELLES

1. NOTATION AND UNITS (see Sketch 1.1)

		SI	*British*
A	aspect ratio of equivalent-wing planform*		
a	lift-curve slope of equivalent-wing planform*	radian^{-1}	radian^{-1}
a_n	lift-curve slope of nacelle in isolation, based on area wl	radian^{-1}	radian^{-1}
c_0	centre-line chord of equivalent-wing planform*	m	ft
$\bar{\bar{c}}$	aerodynamic mean chord of equivalent-wing planform*	m	ft
c_r	root chord of equivalent-wing planform*	m	ft
c_{ref}	general reference chord for stability calculations	m	ft
H	downwash parameter (see Equation (2.3))	radian	radian
K	ratio of lift on nacelle-pylon-fuselage combination to lift on nacelle and pylon in isolation		
l	length of nacelle forward-cowl or overall length of single-cowl nacelle, see Figure 1	m	ft
M	Mach number		
m	fuselage length forward of leading edge of root chord of equivalent wing planform*	m	ft
n	fuselage length aft of trailing edge of root chord of equivalent-wing planform*	m	ft
r	distance of nacelle inlet aft of wing-fuselage aerodynamic centre	m	ft
r'	distance of nacelle inlet aft of quarter-chord point of centre-line chord of equivalent-wing planform*	m	ft
S	area of equivalent-wing planform*	m^2	ft^2
s	semi-span of equivalent-wing planform*	m	ft

For footnote refer to end of Notation.

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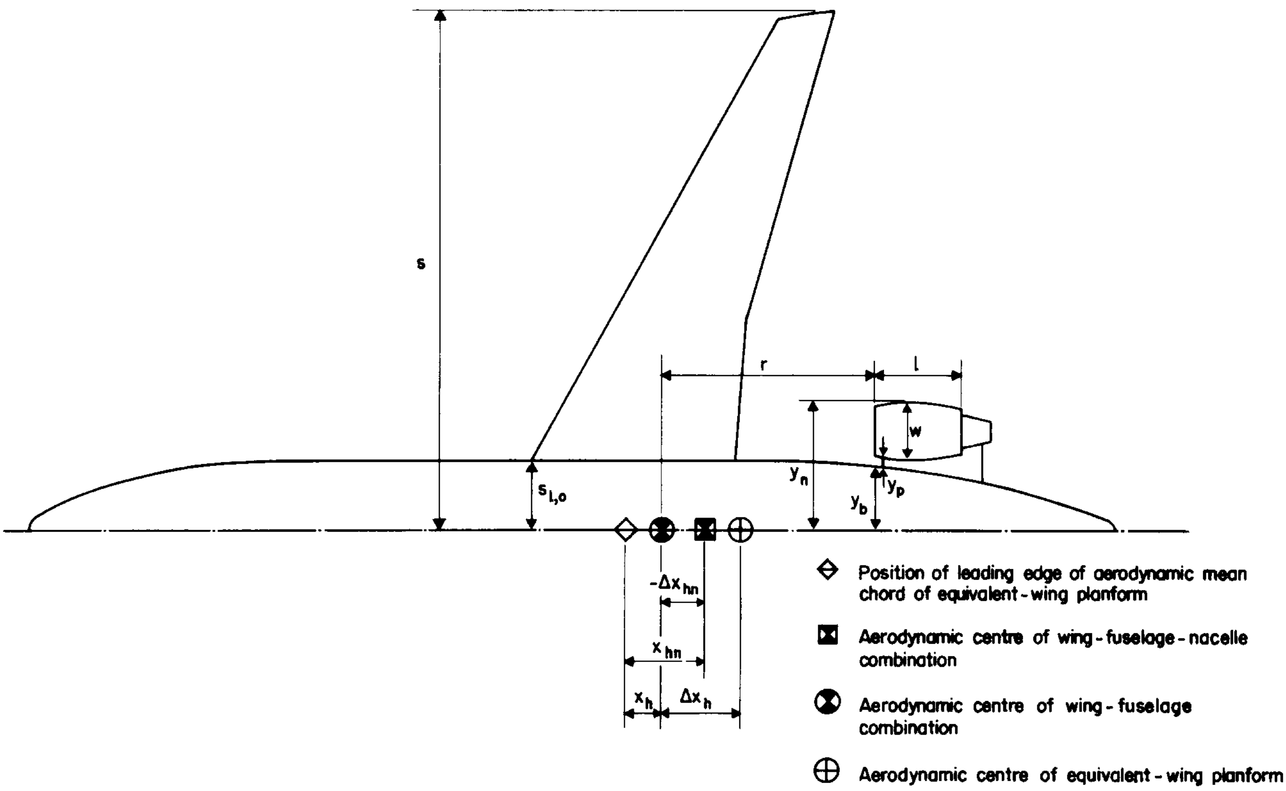
$s_{l,\ 0}$	spanwise distance to side of fuselage planform at point where leading edge of true wing planform meets side of projected fuselage planform*	m	ft
w	maximum spanwise width of single-engine nacelle; half-width of nacelle containing two engines (see Sketches 1.1 and 2.1)	m	ft
$\bar{x}$	chordwise location of aerodynamic centre of equivalent-wing planform, measured positive aft from leading edge of aerodynamic mean chord of equivalent-wing planform*	m	ft
$\bar{\bar{x}}$	chordwise location of leading edge of aerodynamic mean chord of equivalent-wing planform, measured positive aft from apex of equivalent wing planform*	m	ft
x_h	chordwise location of aerodynamic centre of wing-fuselage combination measured positive aft from leading edge of aerodynamic mean chord of equivalent-wing planform*	m	ft
Δx_h	shift in chordwise location of aerodynamic centre due to presence of fuselage (positive forwards)*	m	ft
x_{hn}	chordwise location of aerodynamic centre of wing-fuselage-nacelle combination, measured positive aft from leading edge of aerodynamic mean chord of equivalent-wing planform*	m	ft
Δx_{hn}	shift in chordwise location of aerodynamic centre due to presence of nacelles (positive forwards)	m	ft
y_b	fuselage half-width in plane of nacelle inlet	m	ft
y_n	spanwise location of outer limit of nacelle	m	ft
y_p	width of pylon leading-edge between nacelle and fuselage side	m	ft
β	compressibility parameter, $(1 - M^2)^{½}$		
Λ_0	leading-edge sweep of equivalent-wing planform*	degree	degree
$\Lambda_{¼}$	quarter-chord sweep of equivalent-wing planform*	degree	degree
$\partial\varepsilon/\partial\alpha$	rate of change of downwash angle with incidence at nacelle inlet plane and centre of trailing vortex sheet		

* See Item No.76015 for definition of equivalent-wing planform and calculation of x_h and Δx_h .



Sketch 1.1

2. METHOD

This Item calculates the shift at subsonic speeds in aerodynamic centre position, Δx_{hn}, caused by mounting nacelles on short pylons on the rear fuselage of wing-fuselage combinations. The shift is calculated by treating the nacelles as annular aerofoils located in the wing downwash field and subject to nacelle-fuselage interference effects. The shift is then subtracted from the wing-fuselage aerodynamic centre position x_h, calculated from Item No. 76015, to provide the overall aerodynamic centre position of the wing-fuselage-nacelle combination, x_{hn}. Rear-mounted nacelles cause a rearward shift in the aerodynamic centre position.

In Item No. 76015 the wing-fuselage aerodynamic centre position, x_h, is found by representing the actual gross wing by an equivalent straight-tapered wing, by using item No. 70011 to calculate the aerodynamic centre position, $\bar{x}$, of this equivalent wing and then including a correction term, $-\Delta x_h$, to allow for the forward shift due to the fuselage. The aerodynamic centre position of the wing-fuselage-nacelle combination, measured positive aft from the leading edge of the aerodynamic mean chord of the equivalent-wing planform, is therefore written

$$\frac{x_{hn}}{\bar{\bar{c}}} = \frac{x_h}{\bar{\bar{c}}} - \frac{\Delta x_{hn}}{\bar{\bar{c}}}, \tag{2.1}$$

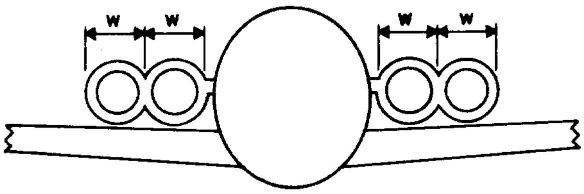
where

$$\frac{x_h}{\bar{\bar{c}}} = \frac{\bar{x}}{\bar{\bar{c}}} - \frac{\Delta x_h}{\bar{\bar{c}}}, \tag{2.2}$$

as calculated from Item No. 76015.

An empirical method for predicting Δx_{hn} has been developed in which the effect of nacelles on the position of the aerodynamic centre is estimated by adapting to nacelle geometries the results given in Derivation 2 for wind-tunnel tests on isolated annular aerofoils, by adding a term to allow for the lift contribution of the pylon and then employing factors to allow for nacelle-pylon-fuselage interference and wing downwash. It is emphasised that the method should not be used for geometries significantly different from those studied in the preparation of this Item (see Section 3.2); in particular Δx_{hn} may be poorly estimated for configurations in which the pylon span is large compared to the nacelle and fuselage widths and the method should not be used when the nacelle leading-edge is very close to or forward of the wing trailing-edge.

The annular aerofoil data are adapted by replacing the aerofoil diameter by the maximum spanwise width of the nacelle. The nacelle lift-curve slope, a_n, which results from this procedure is plotted in Figure 1 as a function of w/l and is taken to be independent of Mach number. For "twin-cowl" nacelles where a forward fan-cowl surrounds the front of a smaller-diameter afterbody (gas generator cowl, possibly with plug), the forward cowl is considered to have the dominating influence and its length is used when estimating a_n. The nacelle lift force is assumed to act at the nacelle lip. The lift contribution of the pylon stubs is approximated by treating the two exposed stubs as a single, low aspect-ratio, rectangular wing of span $2y_p$. Based on the area of the equivalent-wing planform the lift-curve slope of the stubs is then approximately $6y_p^2/S$. For the range of wing-fuselage-nacelle geometries studied in preparing this Item, see Section 3.2, it has proved sufficient for prediction purposes to ignore any interference between the nacelles and pylons. The total lift-curve slope of the nacelles and pylons is then $\{(\Sigma a_n wl) + 6y_p^2\}/S$, where Σ represents the summation of the contribution from each nacelle. For a twin-engine aircraft $\Sigma = 2$, while for a four-engine aircraft with a nacelle containing two engines on each side of the fuselage $\Sigma = 4$ and the dimension w is taken as half the overall nacelle width, see Sketch 2.1.



Sketch 2.1

Because the interference between nacelle and pylon has been ignored the method should be used with caution for nacelle spans larger than those listed in Table 3.1 in Section 3.2. The effect of the fuselage is allowed for by introducing the factor K, the ratio of the total lift on the nacelle-pylon-fuselage combination to the lift on the nacelles and pylons in isolation. For the range of geometries studied a value of $K = 2.4$ has been found to give satisfactory results. This value is comparable to that which would be obtained from slender body theory for a wing-fuselage combination with a wing of semi-span y_n for the range of values $0.35 < y_b/y_n < 0.75$.

The wing downwash is calculated by representing the equivalent wing as an elliptically loaded line vortex located along the wing quarter-chord line with a planar vortex sheet trailing in the free-stream direction (Derivation 1). As rear nacelles are customarily mounted close to the fuselage $(y_p/\bar{\bar{c}} < 0.3)$ and are near to the plane of the wing, the downwash induced by the vortex system is evaluated on the centre-line of the trailing vortex sheet in the plane of the nacelle inlet. The rate of change of downwash angle with incidence is then expressed as

$$\frac{\partial \varepsilon}{\partial \alpha} = \frac{2Ha}{\pi A}, \tag{2.3}$$

where H is plotted in Figure 2 as a function of $\tan\Lambda_{1/4}$ and r'/s and where a, the lift-curve slope of the equivalent wing, is calculated from Item No. 70011.

The net addition to the wing-fuselage lift-curve slope due to the nacelles is therefore

$$\frac{\{\Sigma(a_n wl) + 6y_p^2\}(1 - \partial\varepsilon/\partial\alpha)K}{S} .$$

The additional lift is assumed to act at the nacelle lip and has a moment arm r relative to the wing-fuselage aerodynamic centre position. Therefore the change in aerodynamic centre position, based on the aerodynamic mean chord of the equivalent wing, is given by

$$\frac{-\Delta x_{hn}}{\bar{\bar{c}}} = \frac{\{\Sigma(a_n wl) + 6y_p^2\}(1 - \partial\varepsilon/\partial\alpha)Kr}{Sa\bar{\bar{c}}} , \qquad (2.4)$$

which becomes

$$\frac{-\Delta x_{hn}}{\bar{\bar{c}}} = \frac{2.4\{\Sigma(a_n wl) + 6y_p^2\}(1 - 2Ha/\pi A)r}{Sa\bar{\bar{c}}} , \qquad (2.5)$$

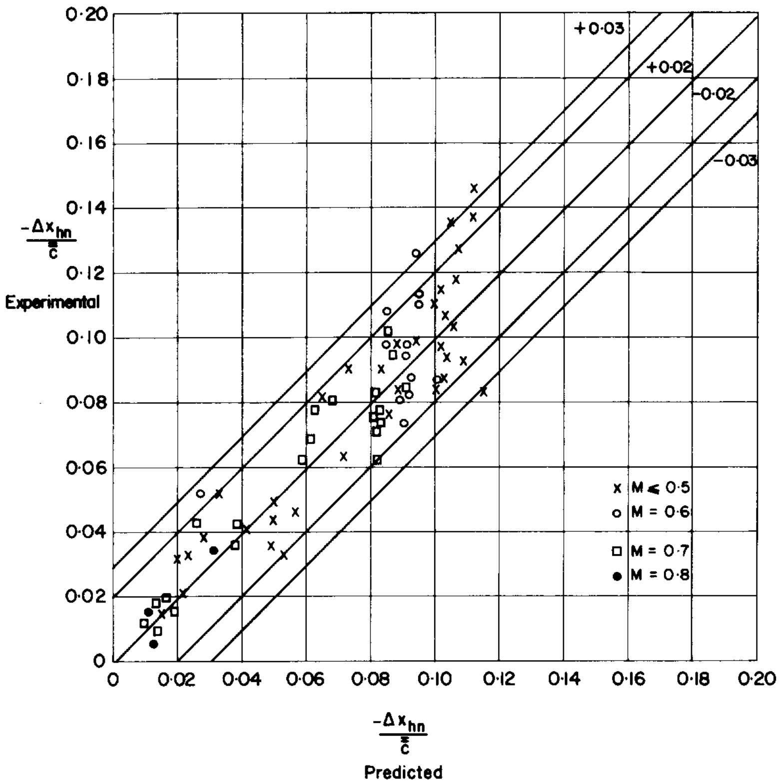
when Equation (2.3) and K = 2.4 are used.

Normally, aircraft stability calculations are referred to a point that is not located at the leading edge of the aerodynamic mean chord of the equivalent wing and may be based on a reference chord, c_{ref}, which is different from $\bar{\bar{c}}$. Item No. 76015 describes how to convert aerodynamic centre positions from Equation (2.1) to a general reference system.

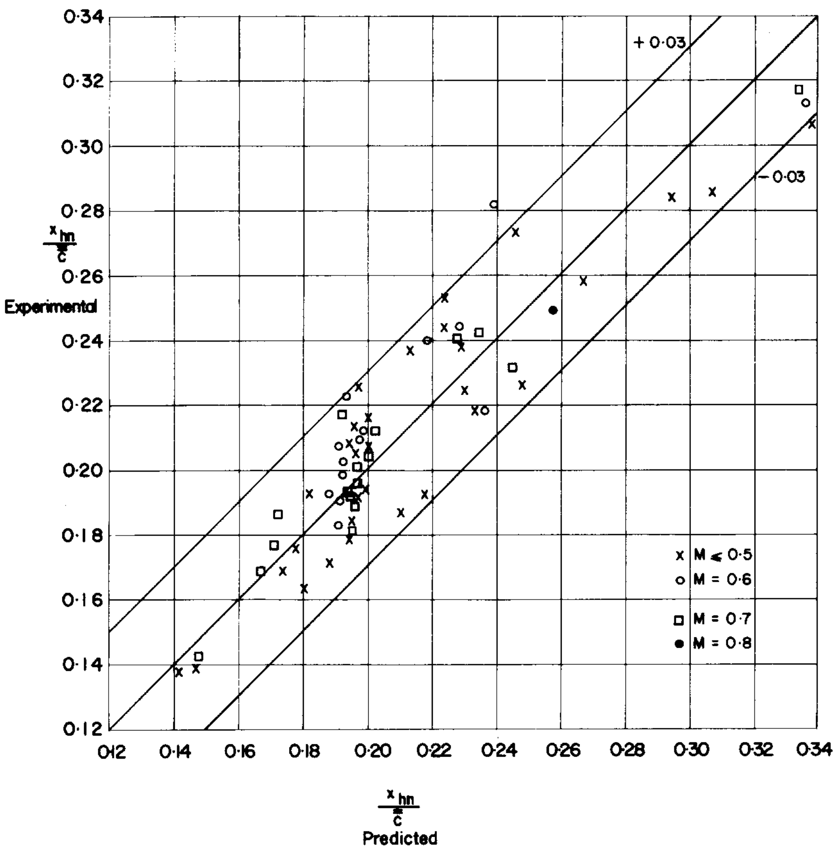
3. ACCURACY AND APPLICABILITY

3.1 Accuracy

The values of $-\Delta x_{hn}$ predicted by Equation (2.5) have been compared with the experimental data from Derivations 3 to 8 for 39 configurations. The agreement between experiment and prediction is shown in Sketch 3.1 and is within $\pm 0.02\bar{\bar{c}}$ for 85 per cent of the data studied. Sketch 3.2 shows the values of x_{hn} predicted by Equation (2.1) plotted against the experimental data from Derivations 3 to 8. The agreement between experiment and prediction is within $\pm 0.03\bar{\bar{c}}$ for 97 per cent of the data studied. This order of agreement is as good as that achieved in Item No. 76015 for predicting the aerodynamic centre position of wing-fuselage combinations.



Sketch 3.1



Sketch 3.2

3.2 Applicability

The method calculates the shift in aerodynamic centre position due to nacelles for conventional rear-fuselage pylon-mounted nacelles, without allowance for tailplane or deployment of wing slats and flaps. It applies at cruise values of lift where the lift-curve slope and the rate of change of pitching moment with lift are both essentially linear. The method assumes that the flow over the configuration is fully attached and wholly subsonic. As the Mach number increases the interference between the nacelle, pylon and fuselage will become subject to local shock waves and the method must therefore be used with caution at high Mach numbers. In general, satisfactory predictions are obtained for Mach numbers below that at which the experimental lift-curve slope and aerodynamic centre position begin to vary rapidly with Mach number. This rapid variation usually commences at a Mach number below and within 0.1 of that at which the experimental lift-curve slope reaches its maximum value.

It should also be noted that the data studied were mainly for tests with free-flow nacelles with mass flow ratios approximately representative of cruise conditions. From the data examined in Item No.77012 for under-wing nacelles and a few data for rear-fuselage nacelles through which the mass flow ratio was altered, it is expected that the prediction of Δx_{hn} will not be sensitive to variations in mass flow within typical ranges of cruise values.

Table 3.1 shows the ranges of nacelle, wing and fuselage parameters studied and care must be exercised if the method is applied to configurations with geometries that are significantly different.

Configurations with pylon spans outside the range covered must be treated carefully as the method may predict Δx_{hn} poorly for nacelles mounted on large-span pylons.

It is important to note that when the nacelle is close to the wing, *i.e.* at or extending forward over the wing trailing-edge, the loading over the wing is affected and the method makes no allowance for this. In addition, the vortex-sheet model used to represent the downwash becomes unrealistic and the estimated values of $(1 - \partial\varepsilon/\partial\alpha)$ are much too low. Consequently, the predicted values of Δx_{hn} seriously underestimate the experimental values. Therefore the method should not be used for configurations where the longitudinal distance between the nacelle lip and the (true) wing trailing-edge is less than $0.3w$ or $0.2\bar{\bar{c}}$ or when r'/s is less than about 0.45.

TABLE 3.1 Range of Geometries Considered

Parameter	*Range*
βA	3.7 to 9.5
$\tan\Lambda_{1/4}$	0.05 to 0.7
$r/\bar{\bar{c}}$	0.9 to 2.4
r'/s	0.45 to 0.8
w/l	0.26 to 1.2
$w/\bar{\bar{c}}$	0.23 to 0.65
y_b/y_n	0.35 to 0.75
$y_p/\bar{\bar{c}}$	0 to 0.28
y_p/w	0 to 0.38 (and 0.6, 0.8)
y_p/y_b	0 to 0.41 (and 0.65)
Inclination of nacelle to wing plane	0 to 3°
Nacelle inlet distance aft of wing trailing edge	$0.3w$ to $3w$ $0.2\bar{\bar{c}}$ to $1.5\bar{\bar{c}}$

4. DERIVATION

The Derivation lists selected sources that have assisted in the preparation of this Item.

1.	SPREITER, J.R. SACKS, A.H.	The rolling up of the trailing vortex sheet and its effect on the downwash behind wings. J. aeronaut. Sci., Vol. 18, No. 1, p.21 January 1951.
2.	FLETCHER, S.H.	Experimental investigation of lift, drag and pitching moment of five annular airfoils. NACA tech. Note 4117, 1957.
3.	PUTNAM, L.E.	Effects of aft-fuselage-mounted nacelles on the subsonic longitudinal aerodynamic characteristics of a twin-turbojet airplane. NASA tech. Note TN D-3781, 1966.
4.	AOYAGI, K. TOLHURTS, W.H.	Large-scale wind-tunnel tests of a subsonic transport with aft engine nacelles and high tail. NASA tech. Note TN D-3797, 1967.
5.	KIRBY, D.A. HEPWORTH, A.G.	Low-speed wind-tunnel tests of the longitudinal stability characteristics of some swept-wing quiet airbus configurations. RAE tech. Rep. 76029, ARC R & M 3801, 1976.
6.	–	Unpublished wind-tunnel data from Aérospatiale.
7.	–	Unpublished wind-tunnel data from Aircraft Research Association.
8.	–	Unpublished wind-tunnel data from British Aerospace, Aircraft Group, Weybridge-Bristol, Hatfield-Chester and Manchester Divisions.

5. EXAMPLE

Find the aerodynamic centre position of the wing-fuselage-nacelle combination shown in Sketch 5.1 for a Mach number of 0.48, based on a reference chord of 4.5 m and referred to a reference point 22.5 m aft of the zero datum axis, which is 4 m ahead of the fuselage nose.

STEP 1: Determine Equivalent Wing Properties, Δx_h and x_h

The aerodynamic centre position of the wing-fuselage combination is calculated by using Item No.76015. (The wing and fuselage shown in Sketch 5.1 are the same as those used in the example in Item No.76015, except that the wing is further aft of the fuselage nose.) The following values are obtained for the equivalent wing planform

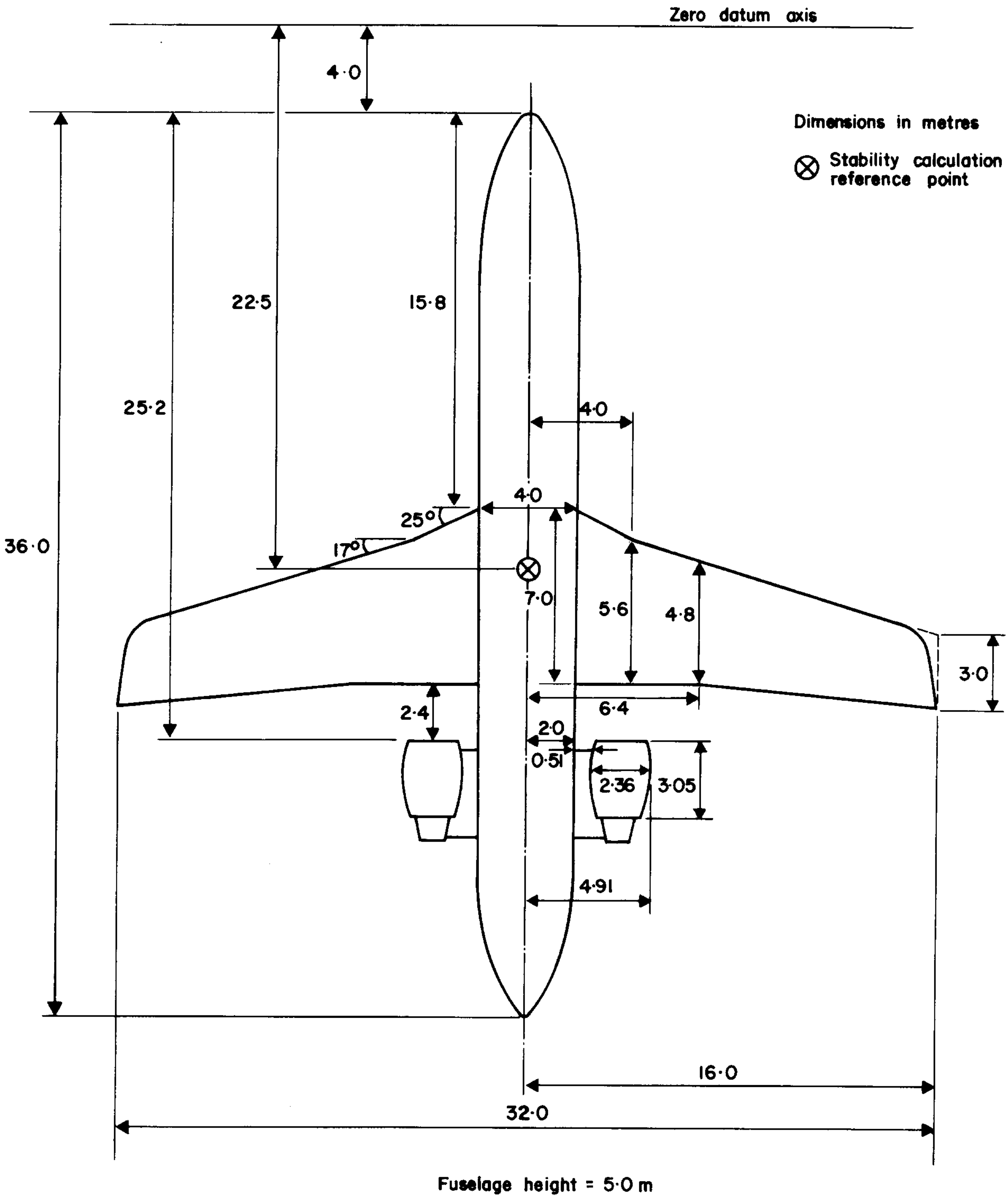
$$
\begin{aligned}
A &= 6.845\,,\\
S &= 149.6\ \text{m}^2,\\
\tan\Lambda_{1/4} &= 0.2567\,,\\
c_r &= 5.931\,\text{m},\\
c_0 &= 6.350\ \text{m},\\
\bar{\bar{c}} &= 4.874\,\text{m},\\
m &= 16.075\,\text{m},\\
n &= 13.994\,\text{m},\\
s_{l,0} &= 2.0\,\text{m},\\
\tan\Lambda_0 &= 0.3091\,,\\
\bar{\bar{x}} &= 2.177\,\text{m}\,,\\
s &= 16.0\ \text{m}\,,\\
\bar{x}/\bar{\bar{c}} &= 0.243\ \text{(using Item No. 70011)}\\
\text{and}\qquad a &= 4.874\ \text{radian}^{-1}\ \text{(using Item No. 70011).}
\end{aligned}
$$

The forward shift in aerodynamic centre position is calculated to be

$$\frac{\Delta x_h}{\bar{\bar{c}}} = 0.150\,.$$

The wing-fuselage aerodynamic centre position is therefore

$$\frac{x_h}{\bar{\bar{c}}} = \frac{\bar{x}}{\bar{\bar{c}}} - \frac{\Delta x_h}{\bar{\bar{c}}} = 0.243 - 0.150 = 0.093\,.$$


Zero datum axis
Dimensions in metres
Stability calculation reference point
4·0
22·5
15·8
25·2
36·0
4·0
4·0
25°
17°
7·0
5·6
4·8
3·0
6·4
2·4
2·0
0·51
2·36
3·05
4·91
16·0
32·0
Fuselage height = 5·0 m

Sketch 5.1

STEP 2: Determine r and r'

From Item No.76015 the distance of the wing-fuselage aerodynamic centre position aft of the fuselage nose is

$$m - s_{l,0}\tan\Lambda_0 + \bar{\bar{x}} + \left(\frac{x_h}{\bar{\bar{c}}}\right)\bar{\bar{c}} = 16.075 - 2.0 \times 0.3091 + 2.177 + 0.093 \times 4.874$$

$$= 18.09 \text{ m.}$$

(Note that $m - s_{l,0}\tan\Lambda_0$ is the distance of the apex of the equivalent-wing planform aft of the fuselage nose.)

The quarter-chord point of the centre-line chord of the equivalent-wing planform aft of the fuselage nose is

$$m - s_{l,0}\tan\Lambda_0 + \frac{c_0}{4} = 16.075 - 2.0 \times 0.3091 + \frac{6.350}{4} = 17.04 \text{ m.}$$

From Sketch 5.1 the plane of the nacelle entry is 25.2 m aft of the fuselage nose, so

$$r = 25.2 - 18.09 = 7.11 \text{ m}$$

and $$r' = 25.2 - 17.04 = 8.16 \text{ m.}$$

STEP 3: Determine that configuration geometry is within the ranges given in Table 3.1

From the previous results and Sketch 5.1 the following values are obtained

$$\begin{aligned}
\beta A &= (1 - 0.48^2)^{1/2} \times 6.845 = 0.8773 \times 6.845 = 6.005\,,\\
\tan\Lambda_{1/4} &= 0.2576\,,\\
r/\bar{\bar{c}} &= 7.11/4.874 = 1.459\,,\\
r'/s &= 8.16/16.0 = 0.51\,,\\
w/l &= 2.36/3.05 = 0.774\,,\\
w/\bar{\bar{c}} &= 2.36/4.874 = 0.484\,,\\
y_b/y_n &= 2.0/4.91 = 0.407\,,\\
y_p/\bar{\bar{c}} &= 0.51/4.874 = 0.105\,,\\
y_p/w &= 0.51/2.36 = 0.216\,,\\
y_p/y_b &= 0.51/2.0 = 0.255\,,
\end{aligned}$$

and the distance of the nacelle inlet aft of the wing trailing-edge is

$$\left(\frac{2.4}{2.36}\right)w = 1.02w\,, \quad \frac{2.4}{4.874}\,\bar{\bar{c}} = 0.492\,\bar{\bar{c}}\,.$$

All of these parameters are within the ranges given in Table 3.1.

STEP 4: Determine Δx_{hn} and x_{hn}

The nacelle lift-curve slope is obtained from Figure 1 at w/l = 0.774 giving

$$a_n = 2.25 \text{ radian}^{-1} .$$

The downwash factor H is obtained from Figure 2 at $r'/s = 0.51$ and $\tan\Lambda_{1/4} = 0.2567$ giving

$$H = 1.42 \text{ radian.}$$

The shift in aerodynamic centre position due to the nacelles is then calculated by Equation (2.5)

$$\begin{aligned}
\frac{-\Delta x_{hn}}{\bar{\bar{c}}} &= \frac{2.4\{(\Sigma a_n w l) + 6y_p^2\}(1 - 2Ha/\pi A)r}{Sa\bar{\bar{c}}} \\
&= \frac{2.4\{(2 \times 2.25 \times 2.36 \times 3.05) + 6 \times 0.51^2\}\left(1 - \dfrac{2 \times 1.42 \times 4.874}{\pi \times 6.845}\right)7.11}{149.6 \times 4.874 \times 4.874} \\
&= \frac{2.4(32.39 + 1.561)(1 - 0.644)7.11}{3553.9} \\
&= 0.058 .
\end{aligned}$$

Therefore, from Equation (2.1), the aerodynamic centre of the wing-fuselage-nacelle combination measured positive aft from the leading edge of the aerodynamic mean chord of the equivalent-wing planform is

$$\begin{aligned}
\frac{x_{hn}}{\bar{\bar{c}}} &= \frac{x_h}{\bar{\bar{c}}} - \frac{\Delta x_{hn}}{\bar{\bar{c}}} \\
&= 0.093 + 0.058 \\
&= 0.151 .
\end{aligned}$$

The aerodynamic centre is now referred to the required stability reference point and based on the required reference chord. The distance of the aerodynamic centre aft of the fuselage nose is

$$\begin{aligned}
m - s_{l,0}\tan\Lambda_0 + \bar{\bar{x}} + \left(\frac{x_{hn}}{\bar{\bar{c}}}\right)\bar{\bar{c}} &= 16.075 - 2.0 \times 0.3091 + 2.177 + 0.151 \times 4.874 \\
&= 18.37 \text{ m.}
\end{aligned}$$

The stability reference point is 22.5 – 4.0 = 18.5 m aft of the fuselage nose, so the aerodynamic centre is 18.5 – 18.37 = 0.13 m forward of the reference point. Based on a reference chord of 4.5 m, the aerodynamic centre is $0.029c_{ref}$ forward of the reference point.

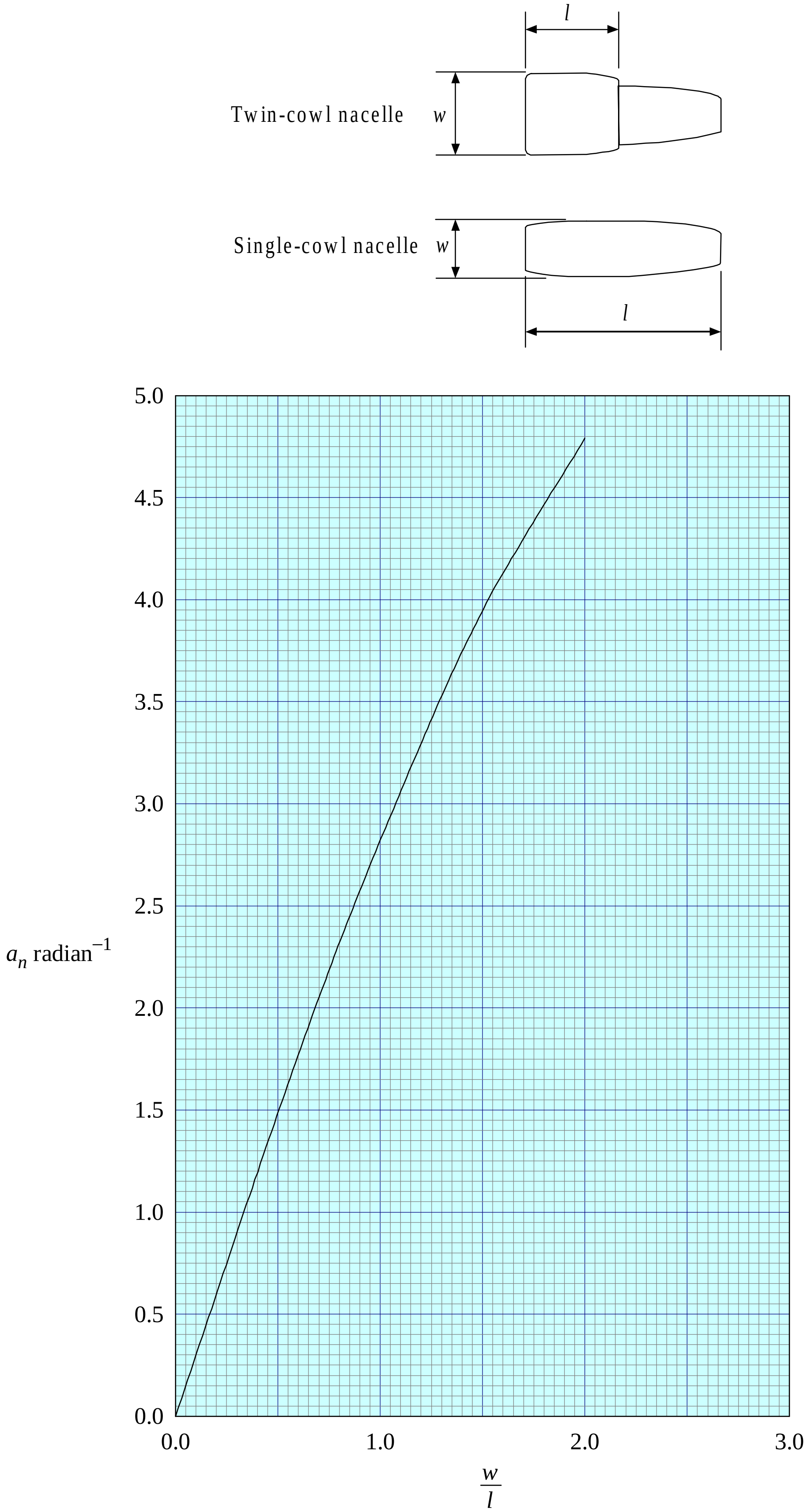


FIGURE 1 LIFT-CURVE SLOPE OF NACELLE

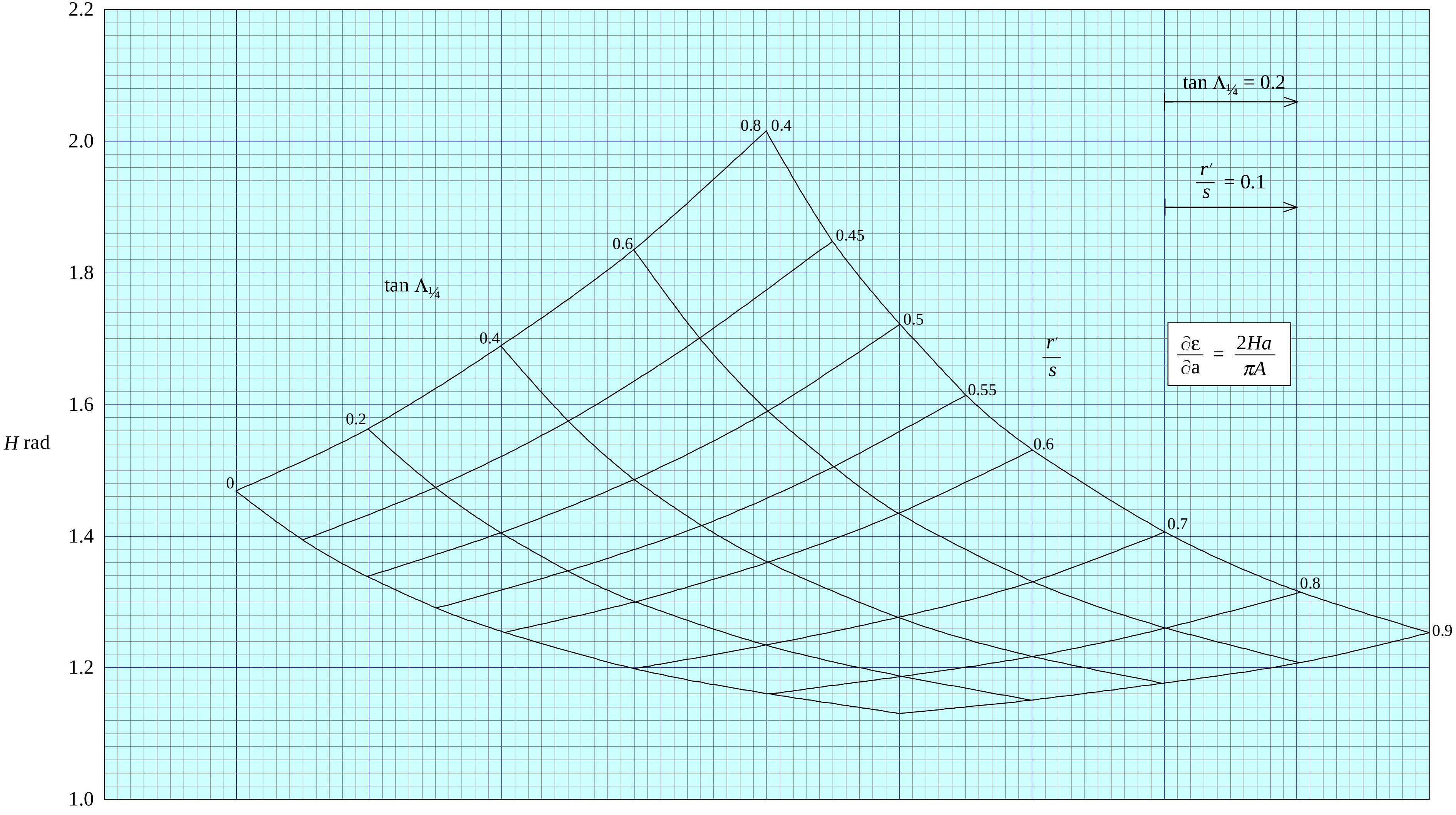


FIGURE 2 DOWNWASH PARAMETER

THE PREPARATION OF THIS DATA ITEM

The work on this particular Item was monitored and guided by the Aerodynamics Committee which first met in 1942 and now has the following membership:

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Mr H. Vogel	–	British Aerospace, Weybridge-Bristol Division.

* Corresponding Members

The work on this Item was carried out in the Aircraft Motion Group of ESDU under the supervision of Mr P.D. Chappell, Group Head. The member of staff who undertook the technical work involved in the initial assessment of the available information and the construction and subsequent development of the Item was

Mr R.W. Gilbey – Senior Engineer.