



ESDU 93034

Issued December 1993
With Amendments A and B
December 1995

Normal force of low-aspect-ratio cropped-delta wings up to high angles of attack at subsonic speeds

Endorsed by
The Royal Aeronautical Society

AVA Documents
Document Sharing Hub

ESDU DATA ITEMS

Data Items provide validated information in engineering design and analysis for use by, or under the supervision of, professionally qualified engineers. The data are founded on an evaluation of all the relevant information, both published and unpublished, and are invariably supported by original work of ESDU staff engineers or consultants. The whole process is subject to independent review for which crucial support is provided by industrial companies, government research laboratories, universities and others from around the world through the participation of some of their leading experts on ESDU Technical Committees. This process ensures that the results of much valuable work (theoretical, experimental and operational), which may not be widely available or in a readily usable form, can be communicated concisely and accurately to the engineering community.

We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

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

Chairman	
Mr H.C. Garner	— Independent
Members	
Mr G.E. Bean*	— Boeing Commercial Airplane Company, Seattle, Wash., USA
Dr N.T. Birch	— Rolls-Royce plc, Derby
Mr K. Burgin	— Southampton University
Mr D. Choo*	— Northrop Corporation, Pico Rivera, Calif., USA
Dr P.C. Dexter	— British Aerospace plc, Sowerby Research Centre, Bristol
Mr J.R.J. Dovey	— Independent
Dr K.P. Garry	— Cranfield University
Dr H.P. Horton	— Queen Mary and Westfield College, University of London
Mr P.K. Jones	— Independent
Mr R. Jordan	— Independent
Mr K. Karling*	— Saab-Scania, Linköping, Sweden
Mr M. Maurel	— Aérospatiale, Toulouse, France
Mr J.B. Newton	— British Aerospace Defence Ltd, Warton
Mr R. Sanderson	— Deutsche Aerospace Airbus, Bremen, Germany
Mr A.E. Sewell*	— McDonnell Douglas, Long Beach, Calif., USA
Mr M.R. Smith	— British Aerospace Airbus Ltd, Bristol.

* Corresponding Member

The technical work in the assessment of the available information and the construction and subsequent development of the Data Item was carried out under contract to ESDU by

Mr A.J. Clarke

NORMAL FORCE OF LOW-ASPECT-RATIO CROPPED-DELTA WINGS UP TO HIGH ANGLES OF ATTACK AT SUBSONIC SPEEDS

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	2
3. METHOD	2
4. APPLICABILITY AND ACCURACY	4
5. DERIVATION AND REFERENCES	5
5.1 Derivation	5
5.2 Reference	7
6. EXAMPLE	8
FIGURES 1 to 4	11 to 23
APPENDIX A NORMAL FORCE OF LOW-ASPECT-RATIO DELTA AND RECTANGULAR WINGS IN THE STALLING AND POST-STALL RANGES OF ANGLE OF ATTACK AT LOW SPEEDS	24
A1. INTRODUCTION	24
A2. STALLING BEHAVIOUR OF LOW-ASPECT-RATIO WINGS	24

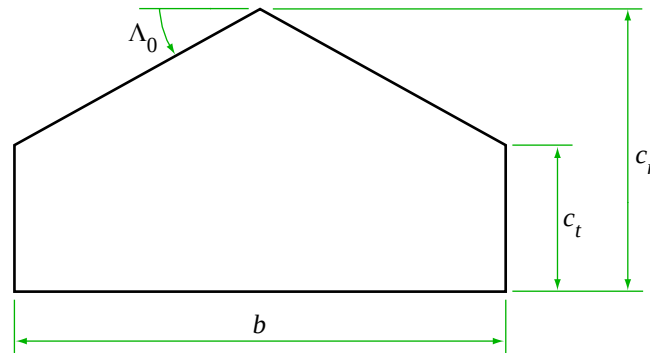
ESDU Copyright material. For current status contact ESDU.

NORMAL FORCE OF LOW-ASPECT-RATIO CROPPED-DELTA WINGS UP TO HIGH ANGLES OF ATTACK AT SUBSONIC SPEEDS

1. NOTATION AND UNITS

		SI	British
A	aspect ratio, b^2/S		
b	wing span, see Sketch 1.1	m	ft
C_L	lift coefficient, $(\text{lift})/\frac{1}{2}\rho V^2 S$		
C_N	normal force coefficient, $(\text{normal force})/\frac{1}{2}\rho V^2 S$		
c_r	root chord, see Sketch 1.1	m	ft
c_t	tip chord, see Sketch 1.1	m	ft
M	free-stream Mach number		
S	planform area, $b(c_r + c_t)/2$	m ²	ft ²
t	maximum thickness of wing	m	ft
V	free-stream velocity	m/s	ft/s
α	angle of attack	degree or radian	degree or radian
β	compressibility parameter, $(1 - M^2)^{1/2}$		
Λ_0	sweepback of leading edge, see Sketch 1.1	degree	degree
λ	taper ratio, c_t/c_r		
ρ	free-stream density	kg/m ³	slug/ft ³

Issued December 1993
 With Amendments A and B, December 1995 – 28 pages
 This page Amendment B



Sketch 1.1 Wing geometry

Some relationships between various geometric parameters are

$$\lambda = \frac{c_t}{c_r}, A = \frac{b^2}{S} = \frac{2b}{c_r + c_t} \text{ and } \tan \Lambda_0 = \frac{4(1 - \lambda)}{A(1 + \lambda)}.$$

2. INTRODUCTION

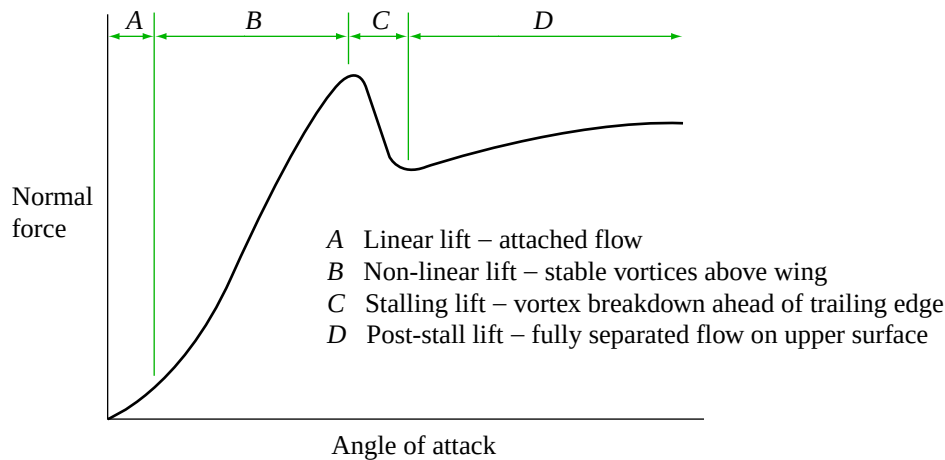
This Item provides a simple semi-empirical means of estimating the normal force on thin, sharp-edged delta or cropped-delta wings of low aspect ratio without camber or twist at angle of attack for Mach numbers up to 0.95.

The method requires only the input of simple geometrical parameters and wing normal-force-curve slope estimated at zero angle of attack. The method itself is described in Section 3, and a guide to its accuracy and applicability is given in Section 4. The use of the method is illustrated by means of a worked example in Section 6. The stalling and post-stall behaviour of delta and rectangular wings, at low speeds, are considered in Appendix A.

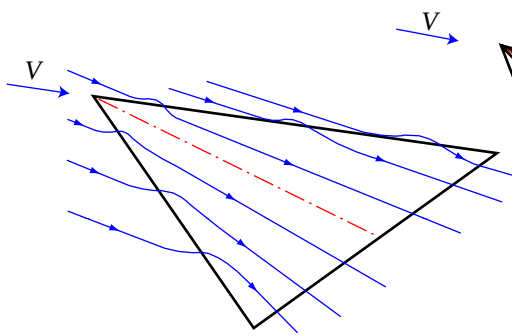
A method for the pitching moment of low-aspect-ratio wings is given in Item No. 95022 (Reference 37), and corresponding methods for normal force and pitching moment at supersonic speeds are given in Item No. 90013 (Reference 36).

3. METHOD

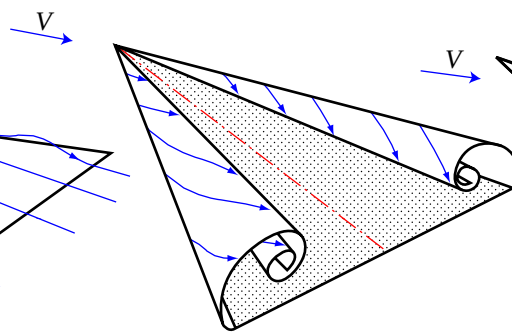
At very low angles of attack the flow around a low aspect ratio wing remains attached and the variation of normal force with angle of attack is essentially linear. As the angle of attack is increased, the flow separates and a coherent and stable vortex system develops, augmenting lift. The nature of the flow in this non-linear regime varies significantly over the range of wing planforms covered by this Item ($0.2 \leq A \leq 4$ and $0 \leq \lambda \leq 1$).



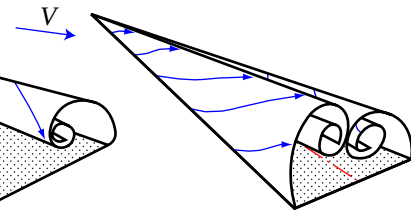
Sketch 3.1a Typical variation of C_N with α for a low-aspect-ratio delta wing



Sketch 3.1b Attached flow



Sketch 3.1c Leading-edge vortex flow



Sketch 3.1d Asymmetric vortex flow

A typical variation of normal force with angle of attack for a low-aspect-ratio delta wing is illustrated in Sketch 3.1a. For such wings, as the angle of attack for attached flow (Sketch 3.1b) is exceeded, the flow separates from the leading edge and rolls up to form a pair of stable, symmetrical vortices over the upper surface of the wing (Sketch 3.1c). The vortex cores extend downstream, gradually increasing in distance from both the wing upper surface and the leading edge, before passing over the trailing edge and, eventually, breaking down. With increasing angle of attack, the vortices intensify, with a corresponding rise in normal force; but when the point of vortex breakdown moves upstream ahead of the trailing edge, there is loss of leading-edge vortex lift with a consequent fall in normal force. Further increase in incidence may again result in rising normal force due to the contributing drag component.

It should be noted that two variations to this flow development may occur. Firstly, for wings of very high leading-edge sweep ($\Lambda_0 > 75^\circ$), the close proximity of the leading-edge vortices may result in vortex contact occurring before vortex breakdown. This produces a vertical displacement of the vortex cores away from the upper surface of the wing, thus curtailing the development of non-linear normal force. With increasing angles of attack the vortices develop asymmetrically (Sketch 3.1d). Secondly, for non-slender wings of moderately low sweep ($\Lambda_0 > 60^\circ$), vortex breakdown is present ahead of the trailing edge as soon as the leading-edge vortices are formed. However, increasing angle of attack does still continue to increase normal force until vortex breakdown reaches the wing apex. Further discussion on vortex breakdown and its influence on normal force is given in Appendix A.

Generally, the above description also applies to cropped-delta wings, but the flow around the streamwise tips also contributes to the vortex system above the wing. However, the flow around rectangular wings and wings with small leading-edge sweep is more complex and geometry dependent. For very low aspect ratios, the flow is dominated by a pair of tip (or side-edge) vortices which, with increasing angle of attack, may break away from the upper surface so that further tip vortices may develop. Such wings can achieve very high angles of attack before the flow breaks down. As aspect ratio increases, the wing fails to sustain lift because the flow becomes dominated by inboard leading-edge stall.

The method of this Item extends up to an angle of attack at which the peak value of normal force is approached. However, Appendix A gives an approximate method for normal force of very thin delta and rectangular wings, say $t/c_r \leq 0.02$, at low speeds at angles of attack up to 90 degrees.

Figures 1, 2 and 3 present data for the direct estimation of normal force coefficient for wings at Mach numbers of 0.5 and below, 0.8 and 0.95, respectively. Each Figure is sub-divided for taper ratios of 0, 0.25, 0.5 and 1, and in each case the variation of C_N with angle of attack and aspect ratio is given in carpet form. Estimates for intermediate values of taper ratio and Mach number may be obtained by cross-plotting. To obtain accurate estimates at very low angles of attack a value for the normal-force-curve slope is required, and this may be obtained either from test data or from Figure 4, which was derived in terms of βA and λ from ESDUpac A7011 for the method of Item No. 70011 (Derivation 30) on the basis that $[dC_N/d\alpha]_{\alpha=0} = [dC_L/d\alpha]_{\alpha=0}$.

4. APPLICABILITY AND ACCURACY

The method of this Item is restricted to thin (say, $t/c_r \leq 0.05$), sharp-edged, uncambered and untwisted wings with straight leading edges, straight unswept trailing edges and, where appropriate, streamwise tips.

The majority of data used to produce Figures 1 to 3 were for flat-plate type wings with sharp chamfered edges. In the case of Derivations 33 and 34, which provided data from large parametric test programmes, the chamfer angles were 30 degrees, measured normal to the leading and trailing edges.

The data relate to monoplane wings, but will be applicable to cruciform configurations with a pair of wings in the vertical plane of symmetry. Although the edges of the vertical wings do contribute to normal force, the edge forces are relatively minor for most of the wing geometries covered by this Item. They may, however, become significant in the case of wings of very low aspect ratio where the wing thickness is a significant proportion of the span.

In the development of this Item attempts were made to extend the method beyond regions A and B of Sketch 3.1a. However, the relatively few test studies that extended to sufficiently high angles of attack demonstrated very considerable discrepancies between the peak values of normal force and corresponding angles of attack for nominally identical planforms. This was most notable for the large parametric set of data from Derivation 33 which, in some cases, gave less than half the peak value of normal force indicated by other sources. However, Derivation 26 provided a study which concentrated on the vortex breakdown and stalling behaviour of very thin, sharp-edged delta wings. The data of Derivation 26 have been used to provide a method for post-stall normal force at low speeds in Appendix A. Additionally, the data of Item No. 70015 (Derivation 31) have been used to provide a corresponding method for rectangular wings.

Figures 1 to 3 represent the test data for C_N of Derivations 1 to 29 and 32 to 35 to within about ± 5 per cent. At very low angles of attack the accuracy is determined by the reliability of the estimated normal-force-curve slope. Most of the continuous curves in Figures 1 to 3 extend to angles before the peak value of normal force is reached. The broken curves are included to aid interpolation in taper ratio and Mach number, but are not directly supported by experimental data.

5. DERIVATION AND REFERENCES

5.1 Derivation

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

1. FLACHSBART, O. Messungen an ebenen und gewölbten Platten Ergebnisse der Aerodynamischen. Versuchsanstalt zu Göttingen, IV, Lief, 1932.
2. TOSTI, P. Low-speed static stability and damping-in-roll characteristics of some swept and unswept low-aspect-ratio wings. NACA tech. Note 1468, 1947.
3. ANDERSON, A.E. An investigation at low speed of a large-scale triangular wing of aspect ratio two. I – Characteristics of a wing having a double-wedge airfoil section with maximum thickness at 20-percent chord. NACA RM A7F06 (TIL 1443), 1947.
4. ROSE, L.M. Low-speed investigation of a small triangular wing of aspect ratio 2.0. I – The effect of combination with a body of revolution and height above a ground plane. NACA RM A7K03 (TIL 1910), 1948.
5. ROSE, L.M. Low-speed investigation of a small triangular wing of aspect ratio 2.0. II – Flaps. NACA RM A7L11 (TIL 1909), 1948.
6. ROSE, L.M. Low-speed investigation of a small triangular wing of aspect ratio 2.0. III – Static stability with twin vertical fins. NACA RM A8C03 (TIL 1908), 1948.
7. STEPHENSON, J.D.
AMUEDO, A.R. Tests of a triangular wing of aspect ratio 2 in the Ames 12-foot pressure wind tunnel. II – The effectiveness and hinge moments of a constant-chord plain flap. NACA RM A8E03 (TIL 1916), 1948.
8. KOLBE, C.D.
TINLING, B.E. Tests of a triangular wing of aspect ratio 2 in the Ames 12-foot pressure wind tunnel. III – The effectiveness and hinge moments of a skewed wing-tip flap. NACA RM A8E21, 1948.
9. WHITTLE, E.F.
LOVELL, J.C. Full-scale investigation of an equilateral triangular wing having 10-percent-thick biconvex airfoil sections. NACA RM L8G05 (TIL 1924), 1948.
10. ANDERSON, A.E. Chordwise and spanwise loadings measured at low speed on large triangular wings. NACA RM A9B17 (TIL 2109), 1949.
11. LANGE/
WACKE Test report on three- and six-component measurements on a series of tapered wings of small aspect ratio (partial report: trapezoidal wing). NACA tech. Memor. 1225, 1949.

12. RIEBE, J.M.
FIKES, J.E. Preliminary aerodynamic investigation of the effect of camber on a 60° delta wing with round and bevelled leading edges.
NACA RM L9F10 (TIL 2178), 1949.
13. SCHOLZ, N. Kraft- und Druckverteilungsmessungen an Tragflächen kleiner Streckung, *Forschung auf dem Gebiete des Ingenieurwesens*, Part B, Vol. 16, No. 3, pp. 85-91, 1949.
14. STIVERS, L.S.
MALICK, A.W. Wind-tunnel investigation at Mach numbers from 0.50 to 1.29 of an all-movable triangular wing of aspect ratio 4 alone and with a body.
NACA RM A9L01 (TIL 2315), 1950.
15. HAWES, J.G.
MAY, R.W. Investigation at low speed of the effectiveness and hinge moments of a constant-chord ailerator on a large-scale triangular wing with section modification.
NACA RM L51A26 (TIL 2709), 1951.
16. LOW, L.
STONE, H.N. The subsonic aerodynamic characteristics of wings in combination with slender bodies of revolution.
Cornell Aeronautical Laboratory. Report No. CM-679, 1951.
17. ADLER, A.A. A correlation of theory with experiment for low-aspect-ratio wings at subsonic speeds. Cornell Aeronautical Laboratory. Report No. AF-743-A-4, 1952.
18. STANBROOK, A. The lift-curve slope and aerodynamic centre position of wings at subsonic and supersonic speeds.
RAE tech. Note Aero 2328, 1954.
19. BARTLETT, G.E.
VIDAL, R.J. Experimental investigation of influence of edge shape on the aerodynamic characteristics of low aspect ratio wings at low speeds.
J. aeronaut. Sci., Vol. 22, No. 8, pp. 517-533, August 1955.
20. NELSON, W.H.
McDEVITT, J.B. The transonic characteristic of 22 rectangular, symmetrical wing models of varying aspect ratio and thickness.
NACA tech. Note 3501, 1955.
21. EMERSON, H.F. Wind-tunnel investigation of the effects of clipping the tips of triangular wings of different thickness, camber and aspect ratio – transonic bump method.
NACA tech. Note 3671, 1956.
22. FINK, P.T. Wind-tunnel tests on a slender delta wing at high incidence.
Z. Flugwissenschaften, Jahrg. 4, Heft 7, pp. 247-249, July 1956.
23. PECKHAM, D.H. Low-speed wind-tunnel tests on a series of uncambered slender pointed wings with sharp edges.
ARC R & M 3186, 1958.
24. LAWFORD, J.A.
BEAUCHAMP, A.R. Low-speed wind-tunnel measurements on a thin sharp-edged delta wing with 70° leading-edge sweep, with particular reference to the position of leading-edge vortex breakdown.
RAE tech. Note Aero 2797, 1961.
25. BREBNER, G.G.
WYATT, L.A.
ILOTT, G.P. Low-speed wind-tunnel tests on a series of rectangular wings of varying aspect ratio and aerofoil section.
RAE TR 65236, 1965.

This page Amendment B

26. WENTZ, W.H. Wind tunnel investigations of vortex breakdown on slender sharp-edged wings.
NASA CR 98731, 1968.
27. KIRBY, D.A. An experimental investigation of the effect of planform shape on the subsonic longitudinal stability characteristics of slender wings.
ARC R & M 3568, 1969.
28. KIRBY, D.A.
KIRKPATRICK, D.L.I. An experimental investigation of the effect of thickness on the subsonic longitudinal stability characteristics of delta wings of 70 degrees sweep-back.
RAE TR 69256, 1969.
29. WOODGATE, L.
HALLIDAY, A.S. Measurements of lift, drag and pitching moment on a series of three delta wings and two square wings.
NPL Aero Report 1289, 1969.
30. ESDU Lift-curve slope and aerodynamic centre position of wings in inviscid subsonic flow.
ESDU International, Item No. 70011, 1970.
ESDUpac A7011.
31. ESDU Fluid forces and moments on flat plates.
ESDU International, Item No. 70015, 1970.
32. HOERNER, S.F.
BORST, H.V. *Fluid-Dynamic Lift*, Sections 17 and 18.
Published by Mrs Liselotte Hoerner, 1975.
33. BRIGGS, M.M.
REED, R.E.
NIELSEN, J.N. Wing alone aerodynamic characteristics to high angles of attack at subsonic and transonic speeds.
NEAR TR 269, 1982.
34. ARA/RAE Unpublished data, 1982.
35. ISAACS, D. Store carriage loads at subsonic speeds. Part 2: Prediction of store wing and fin loads.
RAE TR 88011, 1988.

5.2 Reference

The References provide information supplementary to that given in this Item.

36. ESDU Normal force and pitching moment of low aspect ratio cropped-delta wings up to high angles of attack at supersonic speeds.
ESDU International, Item No. 90013, 1990.
37. ESDU Pitching moment of low-aspect-ratio cropped-delta wings up to high angles of attack at subsonic speeds. ESDU International, Item No. 95022, 1995.