fect on the "randomness" of the sensed turbulence. The foregoing does not fully model the presence of the boundary, but its neglect is not crucial to the general results of the analysis.

Acknowledgments

This research was supported in part by NASA Langley Research through the ASEE Summer Faculty Program. The author acknowledges the collaboration of Drs. R. L. Bowles, B. T. MacKissick, and K. Chuang.

References

[1]Treviño, G., "Turbulence of Flight Simulation," *Journal of Aircraft,* Vol. 23, April 1986, pp. 348-349.

[2]Campbell, C. W. and Sanborn, V. A., "A Spatial Model of Wind Shear and Turbulence," *Journal of Aircraft,* Vol. 21, Dec. 1984, pp. 929-935.

[3]Batchelor, G. K., "Theory of Axisymmetric Turbulence," *Proceedings of the Royal Society Series A,* Vol. 186, 1946, pp. 480-502.

[4]Deissler, R. G., "Effects of Inhomogeneity and of Shear Flow in Weak Turbulent Fields," *The Physics of Fluids,* Vol. 4, Oct. 1961, pp. 1187-1198.

[5]Batchelor, G. K., *Theory of Homogeneous Turbulence,* Cambridge University Press, Cambridge, U.K. 1967, pp. 99-102.

Lower-Side Normal Force Characteristics of Delta Wings at Supersonic Speeds

Erik S. Larson*

FFA, The Aeronautical Research Institute of Sweden Bromma, Sweden

Nomenclature

a = normal force ratio
C_D = drag coefficient
C_L = lift coefficient
C_N = normal force coefficient
C_N^ℓ = wing lower-side normal force coefficient
K = shape factor
M = Mach number in freestream
α = angle of attack
α_n = angle of attack normal to wing leading edge
β = $\sqrt{M^2-1}$
γ = ratio of specific heats
ϵ = wing apex half-angle
Λ_{LE} = wing leading-edge sweep angle
θ = profile apex half-angle

Subscripts

α = slope vs angle of attack
ℓ = lower surface
$(\ )_p$ = attached (potential) flow
nf = normal to disk front surface

Received April 10, 1986; revision received May 6, 1986.

*Senior Research Engineer, Aerodynamic Department. Member AIAA.

Introduction

DURING work with an engineering method for estimating characteristics of flat, sharp leading-edge delta wings at supersonic speeds, it became clear that the lower-side normal force contribution could be reasonably well represented by a two-term expression analogous to the long applied estimation of the normal force of slender bodies. Use is made of experimental data from several sources: the lower-side normal force characteristics over the incidence presented by Wood and Miller[1,2]; the lift curve slope results obtained by Lampert[3]; and Hoerner's[4] compilation of data on disks, analytically represented in Ref. 5. For lack of an accurate estimate of the lift curve slope of the lower-side contribution, an empirical assumption had to be made in the work presented here. This weakness of the present result can be removed sooner or later.

Analytical Expressions

Working from the results of Wood and Miller[1,2] concerning the normal force contribution of the lower side of the wing in the restricted interval, $0.5<\beta \tan\epsilon<1$, a possible and simple representation of the partial coefficient is

$$C_N^\ell = (C_{N_\alpha}^\ell)_p \sin\alpha \cos\alpha + C_{D_{nf}} \sin^2\alpha \leq C_{D_{nf}} \tag{1}$$

where the first term is the lower side normal force curve slope expressed by

$$(C_{N_\alpha}^\ell)_p = a_\ell C_{N_\alpha} \tag{2}$$

characterizing the potential-flow-like part of the normal force. $C_{N_\alpha} \simeq C_{L_\alpha}$ is obtained from experiments by Lampert.[3] The second term represents the nonlinear contribution to the lower-side normal force. The coefficient is the face drag coefficient of a disk in a flow normal to the disk. The coefficient is compiled by Hoerner[4] from experiments and is represented analytically including a Mach number correction in Ref. 5. The expressions are

$$C_{D_{nf}} = \frac{K(q''/q)-2(1-K)}{\gamma M^2} \tag{3}$$

where

$$\frac{q''}{q} = 1.84 - \frac{0.76}{M^2} + \frac{0.166}{M^4} + \frac{0.035}{M^6} + \ldots \tag{4}$$

and

$$K = 0.935 - 0.023\left[1-\left(1-\frac{1}{M^2}\right)^{1/4} \times \left(\frac{M-3}{0.25+|M-3|}\right)^{3/5}\right], \qquad M>0.8 \tag{5}$$

Equation (4) is the gasdynamic relation between the stagnation pressures at the face surface and in the freestream.

At high angles of attack, the terms in Eq. (1) will add up to a sum larger than the front face drag of disks at 90 deg. This is not realistic; therefore, C_N^ℓ is limited as shown in Eq. (1). It might be assumed that the overshoot is precisely compensated by a corresponding loss in the potential flow contribution; however, this situation will not occur because only angles of attack well below 45 deg are treated here.

Equations (1) and (2), after inserting $a_\ell = 0.41$ and calculating the angles of attack normal to the leading edge [$\alpha_n = \tan^{-1}(\tan\alpha/\sin\epsilon)$], give the curves shown in Fig. 1. The Mach number dependency is quite large for the less swept wings and decreases markedly for increasing sweep.

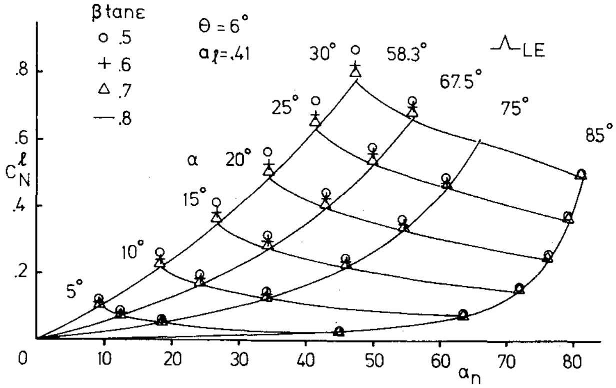

Fig. 1 Mach number dependency of $C_N^\ell(\Lambda_{LE}, \beta\tan\epsilon)$ vs α_n according to Eqs. (1-5) for $0.5<\beta\tan\epsilon<0.8$.

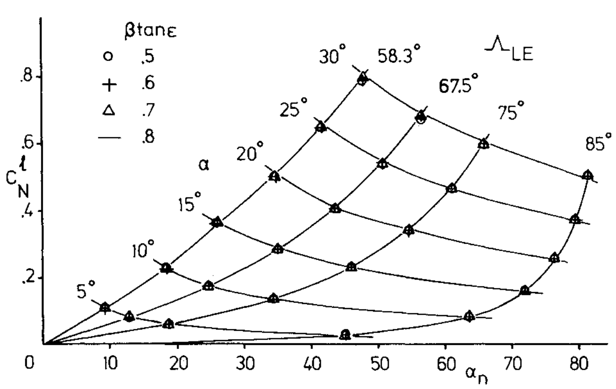

Fig. 2 Collapse of $C_N^\ell(\Lambda_{LE}, \beta\tan\epsilon)$ vs α_n in Fig. 1 into $C_N^\ell(\Lambda_{LE}, 0.7)$ vs α_n by means of Eq. (6).

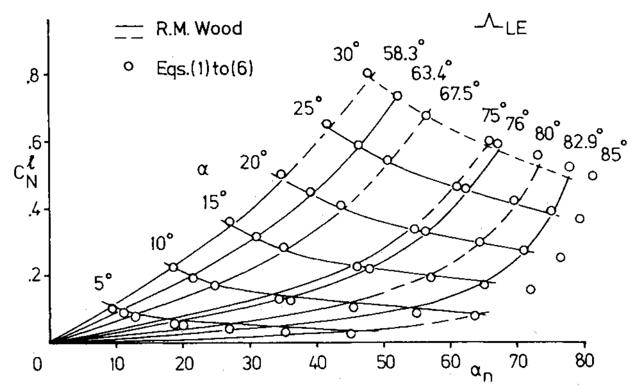

Fig. 3 Representation of $C_N^\ell(\Lambda_{LE}, M)$ vs α_n for flat, sharp leading-edge delta wings according to R. M. Wood[6] by Eqs. (1-6).

The result is perhaps not too surprising because, in reality, the ratio a_ℓ is certainly Mach number dependent. In order to meet the important observation made in Refs. 1 and 2 that C_N^ℓ is almost independent of the Mach number in the interval, an improved assumption about a_ℓ is needed. By means of a set of original data received by courtesy of Dr. R. M. Wood,[6] an empirical modification was applied

$$a_\ell = 0.41\,[1+(\beta\tan\epsilon - 0.7)\sqrt{\sin\epsilon}] \tag{6}$$

With $\beta\tan\epsilon = 0.7$, each set of points in Fig. 1, for a specified angle of attack and sweep angle, collapse into the point for $\beta\tan\epsilon = 0.7$ that falls on or just below the curve for $\beta\tan\epsilon = 0.8$. (See Fig. 2). The result is satisfactory even though a_ℓ is not adequately represented by Eq. (6); however, Eq. (6) can be used as a simple interim approximation in the interval $0.5<\beta\tan\epsilon<1$.

Results and Discussion

The lower-side normal force coefficient data received from R.M. Wood[6] are shown in Fig. 3 as full line and broken line curves. The coefficient C_N^ℓ vs α_n and vs constant α (α cross curves) is shown for several sweep angles, $\Lambda_{LE} = 58.3$-85 deg. The present result of Eqs. (1-6), with lift curve slopes from Ref. 3 for sharp leading-edge delta wings with a wedge half-angle of $\theta = 6$ deg in the flow direction, is represented by the symbols. The symbols correspond to the points for $\beta\tan\epsilon = 0.7$ (triangular symbols) in Fig. 2, obtained by use of Eq. (6) in order to suppress the Mach number dependency of Eqs. (1-5).

From Fig. 3, it is seen that the general trend of $C_N^\ell(\alpha_n, \Lambda_{LE})$ is reproduced by Eqs. (1-6). A closer look at the α cross curves discloses an almost systematic underprediction of the data received from R. M. Wood[6] for small α and large Λ_{LE}. The relative discrepancy is largest at $\alpha = 5$ deg and increases with increasing sweep angle. An increase of the influence of sweep angle in Eq. (6) would improve the correlation at small α, but could hardly be a conclusive explanation of other differences. Here, it can be pointed out only that, on the one hand, Eq. (6) is uncertain and that, on the other hand, the estimation of C_N^ℓ from experiments or by linearized theory is also uncertain. A viscous flow theory to assist in the evaluation of experimental results is probably needed to obtain an adequate expression for a_ℓ to replace Eq. (6).

Conclusions

A simple analytic representation of the lower-side normal force characteristics of flat, sharp leading-edge delta wings at supersonic speeds is presented. The correlation with the available experimental data is encouraging. The result is applicable for Mach numbers above the lower limit for conical flow and below that for supersonic leading-edge flow.

Acknowledgment

This work is sponsored by the Material Administration of the Armed Forces, Air Material Department, Missiles Directorate, Sweden, under Contract AU-2154.

References

[1]Wood, R. M. and Miller, D. S., "Assessment of Preliminary Prediction Techniques for Wing Leading-Edge Vortex Flows at Supersonic Speeds," *Journal of Aircraft*, Vol. 22, June 1985, pp. 473-478.

[2]Wood, R. M., and Miller, D. S., "Fundamental Aerodynamic Characteristics of Delta Wings with Leading-Edge Vortex Flows," *Journal of Aircraft*, Vol. 22, June 1985, pp. 479-485.

[3]Lampert, S., "Normal-Force Characteristics of Delta Wings at Supersonic Speeds," *Journal of the Aeronautical Sciences*, Vol. 24, Sept. 1957, pp. 667-674.

[4]Hoerner, S. F., "Fluid-Dynamic Drag," Hoerner Fluid Dynamics, Brick Town, NJ, 1965, pp. 16-13—16-15.

[5]Larson, E. S., "Crossflow Drag of Finite-Length Rectangular Wing-Bodies," AIAA Paper 85-0451, Jan. 1985.

[6]Wood, R. M., private communication.