Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Trailing Vortex Effects on Following Aircraft

James D. Iversen* and Shmuel Bernstein†
Iowa State University, Ames, Iowa

WIND-TUNNEL tests and a strip-theory analysis have been utilized to estimate the change in lift force and rolling moment on an aircraft due to its penetration into the vortex trail of a leading aircraft. The motivation for this investigation is the effect of the vortex-trail phenomenon on delivery by parachute by similar aircraft flying in in-trail formation.

In the present investigation two one-hundredth scale unpowered models of the Lockheed C-130 transport aircraft were tested in the Iowa State University three-dimensional smoke-tunnel. The two models are shown during testing in Fig. 1. A smoke stream was directed at the nose of the leading model and the approximate vertical location of the trailing model relative to the wake of the leading model was thus obtained from photographs. The trailing model was positioned at various lateral positions relative to the leading model, and also at various vertical positions both above and below the leading model wake. The trailing model support is instrumented for the determination of lift and drag.

Typical experimental results for lift coefficient are shown in Fig. 2. The longitudinal separation of the two models is approximately two span-lengths. The ratio of wing span to test section breadth is 0.44 and the ratio of wing span to test section height is 0.53. Results presented here are interpolated at a Reynolds number (based on mean aerodynamic chord) of about 150,000. The solid line in the figure was calculated from Eq. (1) below. Additional experimental data is presented in Ref. 1.

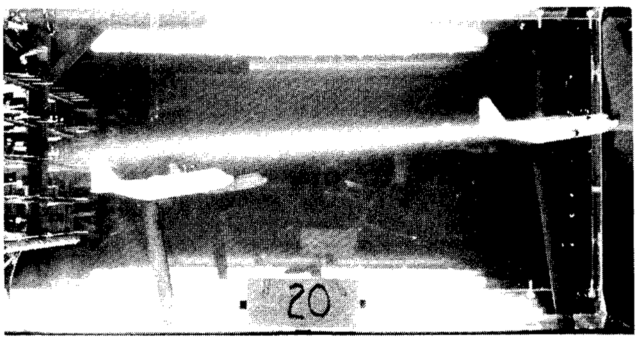

Fig. 1 Wind-tunnel test showing leading and trailing aircraft models and smoke-stream directed at the nose of the leading model.

Received Feb. 23, 1972; revision received March 28, 1973. This work was supported by the Aerospace Engineering Department and the Engineering Research Institute, Iowa State University, Ames, Iowa through funds provided by the Air Force Office of Scientific Research Contract No. F44620-69-6.

Index category: Aircraft Aerodynamics.

*Professor, Aerospace Engineering and Engineering Research Instit. Member AIAA.

†Graduate Student; presently at the Univ. of Washington at Seattle, Wash. Member AIAA.

For the present investigation, a simple strip theory technique, based on Wetmore and Reeder's expression[2] for tangential speed in the trailing vortices, was used to calculate lift and rolling moment on a trailing aircraft flying at various positions relative to the vortex trail and in a direction parallel to the trail. The theory consists simply of calculating the downwash velocity at the line of aerodynamic centers of the following wing due to the leading wing vortex trail, and then assuming that the lift coefficient at each section of the trailing wing is changed by an amount equal to the product of the change in local angle of attack due to the vortex trail and the finite wing lift-curve slope. Spot-checks were made of the results using lifting-line theory and good agreement was attained. The result, using the viscous vortex model of Ref. 2, is

$$\frac{C_L}{C(L)_o} = 1 + \frac{mAR_t}{\pi^2 AR_l}\int_{-1/2}^{1/2} f\left(\frac{y}{b}, \frac{y'}{b'}, \frac{x}{b}, \frac{z}{b}\right)\frac{c'}{b'}\, d\left(\frac{y'}{b'}\right) \tag{1}$$

$$\frac{C_l}{C(L)_o} = \frac{mAR_t}{\pi^2 AR_l}\int_{-1/2}^{1/2} f\left(\frac{y}{b}, \frac{y'}{b'}, \frac{x}{b}, \frac{z}{b}\right)\left(\frac{c'}{b'}\right)\left(\frac{y'}{b'}\right) d\left(\frac{y'}{b'}\right) \tag{2}$$

where

$$f = \frac{\frac{\pi}{8} - \frac{y}{b} - \frac{y'}{b'}\left(\frac{b'}{b}\right)}{\left(\frac{z}{b}\right)^2 + \left[\frac{\pi}{8} - \frac{y}{b} - \frac{y'}{b'}\left(\frac{b'}{b}\right)\right]^2} \times \left\{1 - e^{\left\{\frac{\left(\frac{z}{b}\right)^2 + \left(\frac{y}{b} + \frac{y'}{b'}\left(\frac{b'}{b}\right) - \frac{\pi}{8}\right)^2}{\left(42 + \frac{2.4}{\pi}C(L)_o\frac{S}{b}\frac{\bar{c}}{b}\frac{x}{b}\right)10^{-4}}\right\}}\right\}$$
$$+ \frac{\frac{\pi}{8} + \frac{y}{b} + \frac{y'}{b'}\left(\frac{b'}{b}\right)}{\left(\frac{z}{b}\right)^2 + \left[\frac{\pi}{8} + \frac{y'}{b'}\left(\frac{b'}{b}\right) + \frac{y}{b}\right]^2} \times \left\{1 - e^{\left\{\frac{\left(\frac{z}{b}\right)^2 + \left(\frac{\pi}{8} + \frac{y'}{b'}\left(\frac{b'}{b}\right) + \frac{y}{b}\right)^2}{\left(42 + \frac{2.4}{\pi}C(L)_o\frac{S}{b}\frac{\bar{c}}{b}\frac{x}{b}\right)10^{-4}}\right\}}\right\} \tag{3}$$

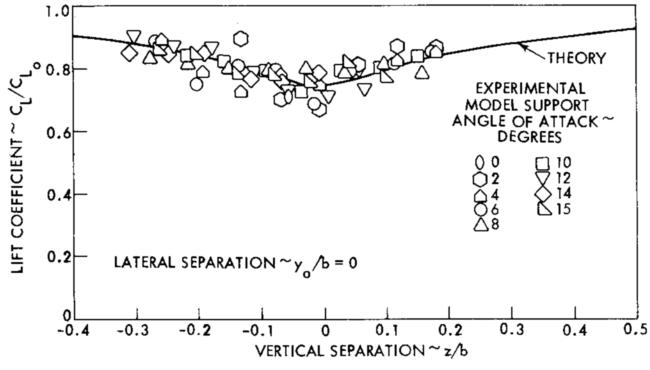

Fig. 2 Ratio of trailing aircraft to leading aircraft lift coefficients, zero lateral separation.

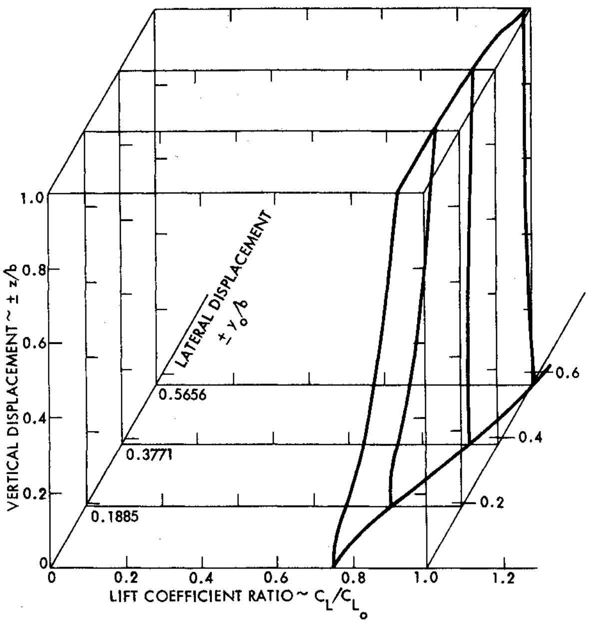

Fig. 3 Trailing aircraft lift coefficient variation with vertical and lateral displacement.

Equations (1) and (2) give the change in lift and rolling moment coefficients of the trailing aircraft wing from the undisturbed equilibrium flight condition (i.e., away from the influence of the leading aircraft trailing vortices). $C(L)_O$ is the lift coefficient of the leading aircraft. The coordinates z and y correspond to the distance of the centerline of the trailing wing below and to the right of the midpoint between the leading aircraft's two trailing vortices. The coordinate x is the longitudinal distance between the leading and trailing aircraft. The primes refer to the local position on the trailing wing with respect to its centerline. AR_t and AR_l are the trailing and leading wing aspect ratios, m the trailing wing lift-curve slope, S, $\bar{c}$, and b are the leading wing's area, mean aerodynamic chord, and wing-span, respectively.

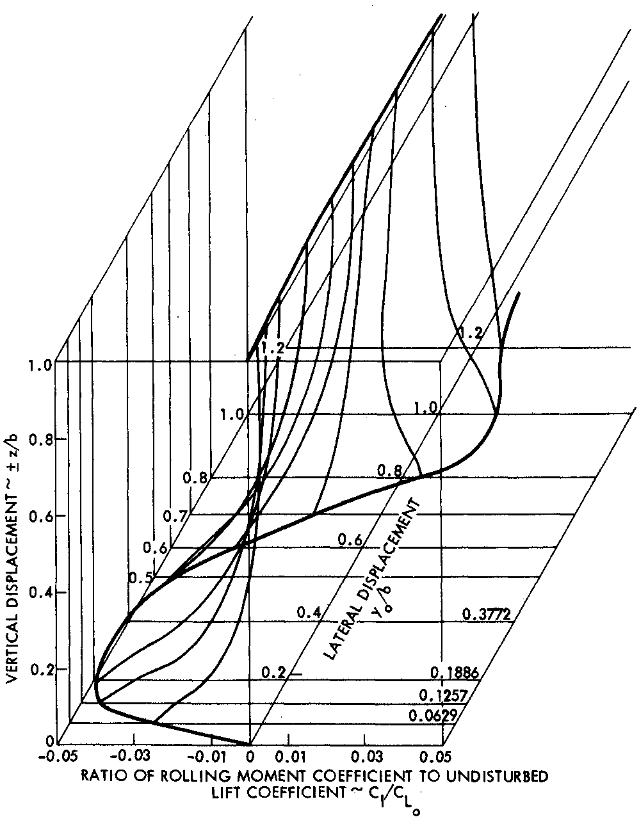

Fig. 4 Trailing aircraft rolling moment variation.

Values of lift and rolling moment coefficient, calculated from Eqs. (1) and (2), are shown in Figs. 3 and 4. These values were used in a three-degree-of-freedom analog computer program simulating the trailing aircraft motion. Results of these simulations which indicate the very erratic motion that can occur have been reported in Ref. 3.

References

[1] Iverson, J. D., "Trailing Vortex Effects on Following Aircraft," ERI-66200, 1970, U. S. Air Force Operations Analysis Standby Unit, Iowa State Univ, Ames, Iowa.

[2] Wetmore, J. W. and Reeder, J. P., "Aircraft Vortex Wakes in Relation to Terminal Operations," TN D-1777, 1963, NASA.

[3] Iverson, J. D. and Bernstein, S., "Dynamic Simulation of an Aircraft under the Effect of Vortex Wake Turbulence," *Annales de l'Association pour le Calcul Analogique*, Vol. 14, 1972, pp. 136–144.

Theoretical Suction and Pressure Distribution Bounds for Flow Separation in Retarded Flow

Tuncer Cebeci* and G. F. Witherspoon†
California State University, Long Beach, Calif.

Nomenclature

A = damping-length constant, see Eq. (6b)
b = parameter, see Eq. (8)
c_f = local skin-friction coefficient, see Eq. (15)
f = dimensionless stream function
L = modified mixing length, see Eq. (6a)
P = pressure-gradient parameter, $(x/u_e)/(du_e/dx)$
$P+$ = dimensionless pressure-gradient parameter, $-(dp/dx)\nu/\rho u^3$
R_x = Reynolds number, $u_e x/\nu$
u, v = x- and y-components of velocity, respectively
v_w+ = dimensionless mass transfer parameter, v_w/u_τ
u = friction velocity, $(\tau_w/\rho)^{1/2} = u_e(c_f/2)^{1/2}$
x, y = rectangular coordinates
ϵ = eddy viscosity
ϵ^+ = dimensionless eddy viscosity, ϵ/ν
η = transformed y-coordinate, see Eq. (9)
μ = dynamic viscosity
ν = kinematic viscosity
ρ = density
τ = shear stress
ψ = stream function

Subscripts

e = outer edge of boundary layer
i = inner region
0 = outer region
w = wall

primes denote differentiation with respect to η.

Received July 6, 1973; revision received October 15, 1973. This work was supported by the National Science Foundation Grant GK-30981.

Index category: Boundary Layers and Convective Heat Transfer Turbulent.

*Adjunct Professor, Mechanical Engineering Department. Member AIAA.

†Graduate Student, Mechanical Engineering Department.