Wing Span Loads of Complex High-Lift Systems from Wake Measurements

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Introduction

HIGH-lift systems of transport aircraft are very complex, usually consisting of a wing with leading-edge devices and multiple slotted trailing-edge flaps. Power plant installations and associated flap cutouts add to the geometric complexity. It is difficult to make accurate wind tunnel measurements of the loads on such a configuration since model flaps are often too small to allow installation of a sufficient number of surface pressure taps. The purpose of this Note is to show that accurate wing span loads can be obtained from wake surveys without the use of pressure taps.

Wake surveys are usually conducted to measure profile drag and vortex drag (e.g., Refs. 1-3) or to gain a qualitative understanding of the flowfield. Such experiments are time-consuming and expensive since a large number of data points must be acquired to get accurate drag data. Performing detailed wake surveys, however, becomes more attractive if the measurements will yield wing span loads in addition to drag.

This Note presents wake data of a twin-engine transport in a takeoff configuration and outlines a method of calculating wing loads based on well-known concepts that relate loading to the strength of trailing vortices.

The method has some features in common with that of El-Ramly and Rainbird,[4] who measured wing span loads on simple wing geometries. It differs in principle from the method of Orloff,[5] who enriches the measured wake data using lifting line theory in order to find the circulation of a wing section. The method described below calculates wing circulation directly from the measured data without recourse to theoretical enrichment.

Wake Measurements

Wake surveys reported here were conducted at low speed (0.22 freestream Mach number) in the Boeing Transonic Wind Tunnel. The test section of this continuous-flow, closed-circuit tunnel is 8 ft high, 12 ft wide, and equipped with corner fillets and 11% slotted walls. A large half-model (52 in. semispan, 12 in. mean aerodynamic chord) of a twin-engine transport with flaps deployed for takeoff and turbine-powered engine simulation was tested. The model was installed vertically on a splitter plate parallel to the tunnel floor (Fig. 1). The primary objective of this test was the measurement of vortex drag on the basis of Maskell's method.[2] The calculation of wing span load was a straightforward extension of the drag data reduction technique.

The measuring system consisted of a single five-hole conical probe (0.25-in. diameter) mounted on a mechanical traverse. The measured data included total pressure and three components of wake velocity. All data were acquired in a measuring plane perpendicular to the tunnel axis and located about two mean aerodynamic chord lengths downstream of the inboard wing trailing edge. Irregular boundaries of the wake survey region (Fig. 1) were chosen to reduce the test time and the number of sampling stations while capturing the complete viscous wake of wing and nacelle. Note that the body flow was not measured. Approximately 20,000 data points with an average spacing of 0.125 in. were recorded during each wake survey. The data were processed after the test.

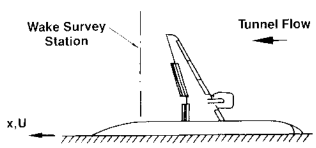
Data Analysis

The first step of the analysis concerns the calculation of wake vorticity from the measured three components of velocity $Q=(U,V,W)$. The streamwise component of vorticity ξ is obtained from its definition

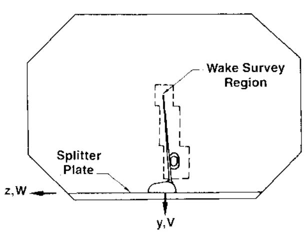
$$\xi = \frac{\partial W}{\partial y} - \frac{\partial V}{\partial z} \tag{1}$$

The symbols y, z and V, W define Cartesian coordinates and, respectively, corresponding velocity components in the measuring plane (Fig. 1). U and ξ are components of velocity and vorticity in the direction of the tunnel freestream. Care must be taken when evaluating this equation numerically. Briefly, the measured velocities are interpolated quadratically to obtain their values at the grid points of a uniform computational grid. Numerical differentiation, preceded by cubic spline smoothing of the cross flow velocities, in turn, provides ξ.

Wake vorticity consists of vorticity shed when lift and side forces are generated as well as the vorticity associated with



a) Side view of half-model.



b) View of test section (looking downstream).

Fig. 1 Installation of transport model in Boeing Transonic Wind Tunnel.

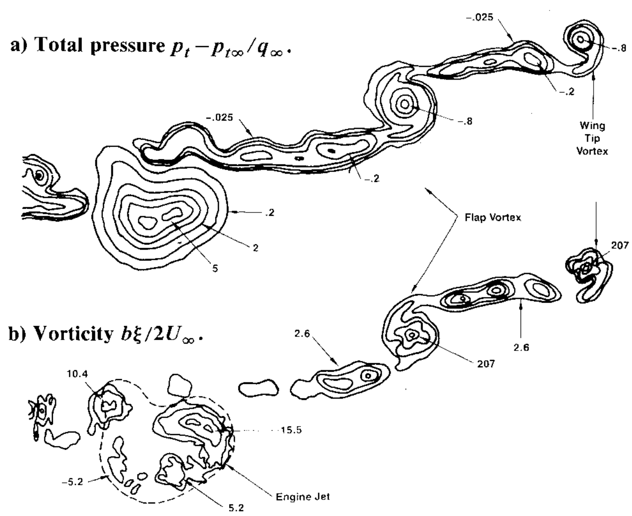


Fig. 2 Measured wake contours.

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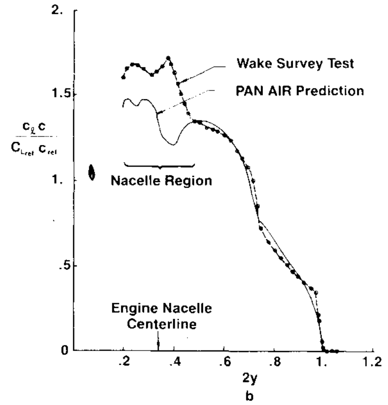

Fig. 3 Spanwise distributions of wing load.

profile drag. The latter vorticity vector is assumed to be confined to the y, z plane and, hence, does not contribute to ξ. The former type of vorticity can be calculated assuming that vortex filaments shed during lift generation are aligned with the local flow. Its magnitude becomes

$$\omega = \frac{|Q|}{U}\xi \tag{2}$$

At this point we imagine the wake to be represented by elemental horseshoe vortices whose bound legs lie on the surface of the model. Both bound and trailing vortex filaments have the circulation $(-\omega)\,dy\,dz$. The increment in wing circulation due to all wake vortex filaments in a spanwise strip of width dy follows from

$$d\Gamma' = \int_{\text{wake}} (-\omega)\,dz\,dy \tag{3}$$

where the integration is performed across the wake in the positive z direction. The circulation of a wing section becomes

$$\Gamma'(y) = \int_{y_R}^{y}\int_{\text{wake}} (-\omega)\,dz\,dy_1 \tag{4}$$

with y_R denoting a station outboard of the wing tip where ω vanishes. The span load can now be obtained from the familiar Kutta-Joukowski formula, $\rho U_\infty \Gamma'(y)dy$ in which ρ, U_∞ denote the density of air and the freestream velocity, respectively. With this information the wingspan load coefficient can be written as

$$\frac{c_\ell c}{C_{L_{\text{ref}}} c_{\text{ref}}} = \frac{2}{C_{L_{\text{ref}}} c_{\text{ref}}}\int_{y_R}^{y}\int_{\text{wake}}\left(-\frac{\omega}{U_\infty}\right)dz\,dy_1 \tag{5}$$

where c_ℓ is the wing load coefficient nondimensionalized by the freestream dynamic pressure and the local wing chord $c(y)$. Note that the load coefficient c_ℓ does not, in general, represent lift alone but is the summation of the forces acting on the bound vortex element whose orientation cannot be determined from wake measurements. In the case of tip fins or nacelles, for example, c_ℓ could contain significant side force components. The symbols $C_{L_{\text{ref}}}$ and c_{ref} denote reference load coefficient and a reference chord, respectively. These can be chosen arbitrarily but must have a consistent definition if span load data from different sources are compared.

The total load of that portion of the configuration between the inboard boundary y_L and the outboard boundary y_R can be calculated from

$$L = \rho U_\infty\left(-\xi(y_L)y_L + \int_{\text{wake}}\int y\omega\,dy\,dz\right) \tag{6}$$

which becomes

$$L = \rho U_\infty \int_{\text{wake}}\int y\omega\,dy\,dz \tag{7}$$

for a complete wake survey of a full model. This last result reduces to Landahl's,[6] valid for small wake deflection, where $\omega \to \xi$.

Results

Examples of the measured wake contours for total pressure and vorticity are shown in Fig. 2. Total pressure p_t is plotted as a deficit defined with freestream values of p_t and normalized by dynamic pressure q_∞. The streamwise component of wake vorticity is nondimensionalized by the freestream velocity and model semispan $b/2$. The wing tip vortex and the strong vortex shed from the outboard edge of the trailing-edge flap system are clearly visible. The vorticity data were used to calculate the span load distribution of Fig. 3. For comparison, inviscid theoretical predictions of the PAN AIR code[7] obtained with a model for powered engine simulation are also shown. These theoretical data represent spanwise lift distribution, scaled by the local wing chord and nondimensionalized by the sum of all lift and side forces in the outboard wing and nacelle region. Good agreement is demonstrated outboard of the nacelle. The large differences in the nacelle region are mainly due to side forces contained in the wake survey data that could not be distinguished from lift.

The accuracy of load data from wake measurements is difficult to assess. One source of error is the deformation of the wake between the wing trailing edge and the survey station. In particular, a lateral shift of vortex filaments will distort the span load distribution. Other uncertainties include the dissipation of wake vorticity, the intrusiveness of the five-hole probe and its mechanical support, and errors of velocity and position measurements. Clearly, additional evaluation of the technique is needed, but the results indicate that the combined effects of the measuring uncertainties is of minor importance. The only significant drawback of this technique seems to be its inability to distinguish between lift and side forces.

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References

[1]Betz, A., "A Method for the Direct Determination of Profile Drag," (in German), *ZFM*, Vol. 16, No. 42, 1925.

[2]Maskell, E. C., "Progress Towards a Method for the Measurement of the Components of the Drag of a Wing of Finite Span," RAE Tech. Report 72232, 1972.

[3]Hallstaff, T. H. and Brune, G. W., "An Investigation of Civil Transport Aft Body Drag Using a Three-Dimensional Wake Survey Method," AIAA Paper 84-0614, 1984.

[4]El-Ramly, Z. and Rainbird, W. J., "Flow Survey of the Vortex Wake behind Wings," *Journal of Aircraft*, Vol. 14, Nov. 1977, pp. 1102-1108.

[5]Orloff, K. L., "Spanwise Lift Distribution on a Wing from Flowfield Velocity Surveys," *Journal of Aircraft*, Vol. 17, Dec. 1980, pp. 875-882.

[6]Landahl, M. T., "Numerical Modeling of Blunt Body Flows—Problems and Propects," *Aerodynamic Drag Mechanisms of Bluff Bodies and Road Vehicles*, edited by G. Sovran et al., Plenum Press, New York, 1978.

[7]Magnus, A. E. and Epton, M. A., "PAN AIR—A Computer Program for Predicting Subsonic or Supersonic Linear Potential Flows About Arbitrary Configurations Using a Higher Order Panel Method," Vol. 1, Theory Document (Version 1.0) NASA CR-3251, 1980.