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Quantitative Low-Speed Wake Surveys

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Theoretical and practical aspects of conducting three-dimensional wake measurements in large wind tunnels are reviewed with emphasis on applications in low-speed aerodynamics. Such quantitative wake surveys furnish separate values for the components of drag such as profile drag and induced drag, but also measure lift without the use of a balance. In addition to global data, details of the wake flowfield as well as spanwise distributions of lift and drag are obtained. This article demonstrates the value of this measurement technique using data from wake measurements conducted on a variety of low-speed configurations including the complex high-lift system of a transport aircraft.

Nomenclature

b = model span
C_D = total drag coefficient
C_{D_i} = induced drag coefficient
C_{D_p} = profile drag coefficient
C_L = total lift coefficient
c = local wing chord
c_{d_i} = wing section induced drag coefficient
c_{d_p} = wing section profile drag coefficient
c_l = wing section lift coefficient
M = Mach number
p = static pressure
p_t = total pressure
q = dynamic pressure
Re = Reynolds number
S = tunnel cross-sectional area
U = axial velocity component
V, W = crossflow velocity components
y, z = Cartesian coordinates in measuring plane
α = angle of attack
ΔC_D = upsweep drag
ξ = axial component of vorticity, Eq. (8)
ρ = density
σ = source, Eq. (9)
Φ = velocity potential, Eq. (11)
Ψ = stream function, Eq. (10)

Subscripts
ft = value per foot
MAC = mean aerodynamic chord
ref = reference condition
∞ = freestream values

Introduction

QUALITATIVE wake surveys employing wake imaging have verified that most aerodynamic flows of interest are stable.[1] Moreover, they can be surveyed economically in large wind tunnels using mechanical traversers and pneumatic probes. Qualitative wake surveys are conducted to visualize the flowfield, which is a prerequisite to a better understanding of aerodynamic performance.

Quantitative three-dimensional wake surveys are a natural extension of wake imaging. They allow separate measurements of profile drag, induced drag, and lift, including spanwise distributions. However, there are significant differences in data acquisition and processing between wake imaging and quantitative wake surveys. The latter requires the use of a pneumatic probe with multiple holes instead of a single total pressure probe to record pressures and velocities which can then be converted into aerodynamic forces. Furthermore, quantitative wake surveys require very accurate probe position measurements since spatial derivatives of flow velocities must be computed during data reduction.

Quantitative wake surveys are of much value to the aerodynamic design of airplanes for the following reasons:

1) They can be used as a diagnostic tool during airplane development to study the effect of configuration changes on the components of drag.

2) Separate measurements of induced drag and profile drag facilitate the prediction of flight drag based on measurements at low Reynolds number wind-tunnel test conditions. This is because induced drag and profile drag are associated with different flow phenomena which must be scaled differently to account for changing Reynolds number.

3) Separate measurements of the components of drag are also of value to the developer of CFD codes since profile drag and induced drag are usually predicted with different aerodynamic flow models which must be validated separately.

This article describes the wake survey technique in use at the Boeing Aerodynamics Laboratory which is based on the work of Maskell[2] and Betz.[4] The underlying theory for the measurement of induced drag and lift had been published by Maskell who also conducted an exploratory wind-tunnel test confirming the validity of his method. The theory for the measurement of profile drag is that of Betz.[3,4]

The wake survey methodology also includes certain features of the work of others. Among them are Wu[5] and Hackett[6,7] who contributed to the theoretical foundation and developed a practical wake survey method with emphasis on applications in automotive engineering.

Several other experimentalists reported quantitative wake surveys. Onorato et al.[8] conducted wake measurements behind models of automobiles, but their drag analysis does not utilize the simplifications introduced by Maskell and Betz. Chometon and Laurent[9] performed wake measurements on a simple wing to investigate the relation between induced drag and vortex drag. Weston[10] of NASA Langley conducted quantitative wake surveys behind wing half-models based on the theory of Maskell and Betz. In his data analysis, Weston focused on the role of vortex cores, and modified the definitions of profile drag and induced drag implementing an earlier proposal of Batchelor.[11] El-Ramly and Rainbird[12–15] published a number of papers describing complete flowfield measurements behind wings from which aerodynamic forces were calculated, but they do not provide details of their theoretical analysis.

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Wakes of two-dimensional airfoils have been routinely measured for many years with the primary objective of getting accurate profile drag data which cannot be obtained from balances. Wake surveys of three-dimensional configurations have occasionally been conducted but are not widely accepted by design aerodynamicists. The main reason for this is a legitimate concern about the cost of such wake measurements which require the measurement of a large number of data points. This can indeed be a time consuming and, hence, expensive process if methods that work so well in two-dimensional wake surveys are applied without further refinements. In addition, three-dimensional wake surveys were suspected to be inaccurate since the desired drag and lift values are the composites of a large number of individual measurements. This article addresses these and other issues and reports on the progress made since Maskell conducted the first wind-tunnel test of this kind at the Royal Aircraft Establishment in the UK some 20 yr ago.

Theory

Assumptions

Aerodynamic forces are calculated from the measured wake flow data assuming the following:

1) Wake flow data are measured in a single plane downstream of the model. This plane, located at the so-called wake survey station (Fig. 1), is assumed to be perpendicular to the wind-tunnel axis. In most wind tunnels, the wake survey station must be moved very close to the model because of test section and hardware limitations.

2) The flow at the wake survey station is steady and incompressible which limits the freestream Mach number in the wind tunnel to about 0.5. This does not turn out to be a serious limitation, as will be discussed later.

3) The flow in the empty wind tunnel is a uniform freestream parallel to the tunnel axis. Any deviations from this ideal wind tunnel, as well as instrumentation misalignments, are assumed to be accounted for by measurements at the wake survey station with the model and its support apparatus removed.

4) The effective ceiling, floor, and side walls of the empty wind tunnel, defined as the geometric walls modified by the displacement thickness of the wall boundary layers developing in the empty tunnel, are such that the tunnel freestream velocity is everywhere tangent to these surfaces. Note that the presence of a model, particularly a model that is large compared to the test section size, will disturb this displacement surface. Also notice that this choice neglects the possible effect of an axial pressure gradient in the empty tunnel (buoyancy).

5) Viscous shear stresses at the wake survey station are neglected.

6) As written, the equations do not account for blowing or suction through the model surface, but could easily be modified.

Components of Drag

With these assumptions, an application of the momentum integral theorem, employing the control volume shown in Fig. 1, provides the following equation for model drag:

$$D = \iint_{\text{wake}} (p_{t_\infty} - p_t)\,\mathrm{d}s + \frac{\rho}{2}\iint_S (V^2 + W^2)\,\mathrm{d}s + \frac{\rho}{2}\iint_S (U_\infty^2 - U^2)\,\mathrm{d}s \tag{1}$$

in which the symbol p_t denotes total pressure and V, W are the components of the crossflow velocity in the measuring plane perpendicular to the tunnel axis. U and ρ denote the velocity in the direction of the tunnel axis and density, respectively. Undisturbed freestream values are indicated by the subscript ∞.

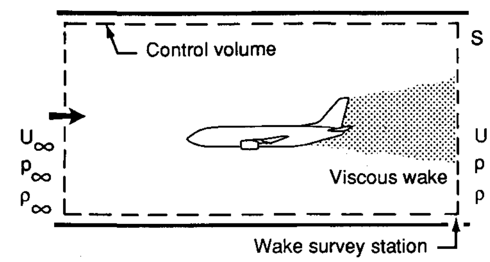

Fig. 1 Control volume for derivation of wake equations.

Here, the first term is an integral of the total pressure deficit which is sometimes used as a measure for profile drag even though it is not the only contribution to this type of drag. As indicated, this integral is limited to the viscous wake since the total pressure deficit is zero outside this region of the flow. The second term, representing the kinetic energy of the crossflow, is termed vortex drag, whereas the third term containing axial velocities does not have any particular name in traditional nomenclature. We will see below that this third term contains contributions to both profile drag and induced drag.

It should be emphasized that Eq. (1) is valid for configurations in locally compressible flow since the assumption of incompressible flow has only been applied to simplify the velocity and pressure terms at the wake survey station and far ahead of the model.

Equation (1) is not well-suited for use in a practical wake measurement technique since only the first integral is limited to the viscous part of the wake. An evaluation of the other two terms would require the measurement of all three velocity components throughout S.

In order to obtain an equation for profile drag which is suitable for practical wake measurements, Betz[4] introduced an artificial axial velocity U^* defined by the equation

$$U^{*2} = U^2 + (2/\rho)(p_{t_\infty} - p_t) \tag{2}$$

Notice that U^* is the same as the true U outside the viscous wake, where the total pressure is p_{t_∞}. If one also introduces a perturbation velocity, defined by $u' = U^* - U_\infty$, drag can be written as the sum of profile drag D_p and induced drag D_i

$$D = D_p + D_i \tag{3}$$

with

$$D_p = \iint_{\text{wake}} \left[p_{t_\infty} - p_t + \frac{\rho}{2}(U^* - U)(U^* + U - 2U_\infty)\right]\mathrm{d}s \tag{4}$$

$$D_i = \frac{\rho}{2}\iint_S (V^2 + W^2 - u'^2)\,\mathrm{d}s \tag{5}$$

The measurement of profile drag can now be conducted economically by measuring total pressure deficit and axial velocity in the viscous wake only.

Motivated by the need to also limit the measurement of induced drag to the viscous part of the wake, Maskell[2] interpreted the axial velocity perturbation term in Eq. (5) as a blockage correction in which blockage velocity is calculated from

$$u_b = \frac{1}{2S}\iint_{\text{wake}} (U^* - U)\,\mathrm{d}s \tag{6}$$

This blockage correction can easily be implemented by replacing the tunnel freestream velocity in the profile drag equation by an effective freestream velocity, $U_e = U_\infty + u_b$.

The elimination of the u' term from the induced drag equation is the most questionable aspect of Maskell's theory since the distinction between vortex drag and induced drag disappears. In principal, the u' term should remain part of induced drag even though it is probably small compared to vortex drag in many applications.[16]

Induced Drag

According to Maskell, the remainder of the induced drag equation can be approximated by

$$D_i \approx \frac{\rho}{2}\iint_{\text{wake}} \Psi\xi \, ds - \frac{\rho}{2}\iint_{S} \Phi\sigma \, ds \tag{7}$$

where the symbol ξ represents the component of wake vorticity in the direction of the tunnel axis, σ is the crossflow divergence or source. They are calculated from the measured V, W using their definitions

$$\xi = \frac{\partial W}{\partial y} - \frac{\partial V}{\partial z} \tag{8}$$

$$\sigma = \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = -\frac{\partial U}{\partial x} \tag{9}$$

Ψ is obtained from a solution of

$$\frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2} = -\xi \tag{10}$$

It describes a flowfield which is induced by the axial component of vorticity. Equation (10) must satisfy the boundary condition $\Psi = 0$ at the tunnel walls so that they become a streamline of this two-dimensional flowfield.

Φ is calculated from

$$\frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = \sigma \tag{11}$$

and the following boundary condition of no flow through the tunnel walls:

$$\frac{\partial \Phi}{\partial n} = 0$$

Notice that the first integral in Eq. (7) is limited to the viscous wake since vorticity vanishes outside. The second term would still require measurements throughout the test section area, but wake measurements behind models of airplane configurations have shown that the source σ is negligibly small outside the viscous wake. Hence, induced drag can be approximated by

$$D_i \approx \frac{\rho}{2}\iint_{\text{wake}} (\Psi\xi - \Phi\sigma) \, ds \tag{12}$$

Lift

The momentum integral theorem together with the control volume of Fig. 1 yields the following equation for lift:

$$L = \iint_{S_4} p \, ds - \iint_{S_3} p \, ds - \rho \iint_{S} WU \, ds \tag{13}$$

where the first two terms represent the difference in static pressure between tunnel floor and ceiling. This integration is performed along upper and lower surfaces of the control volume, denoted respectively by S_3 and S_4. The third term arises from the downwash behind the model. The equation for lift can be cast into the following form (e.g., Refs. 2 and 16):

$$L = \rho U_\infty \iint_{\text{wake}} y\xi \, ds + \rho \iint_{S} (U_\infty - U)W \, ds \tag{14}$$

in which the first integral is expressed in terms of axial vorticity which vanishes outside the viscous wake and, hence, only requires measurements in the wake. In most cases the second integral is expected to be small so that lift can be approximated by

$$L \approx \rho U_\infty \iint_{\text{wake}} y\xi \, ds \tag{15}$$

Instrumentation

Most three-dimensional wake surveys conducted by Boeing employ pneumatic probes with multiple orifices mounted on mechanical traversers. All wake survey tests described in this article used a single five-hole conical probe 0.25 in. in diam (Fig. 2), in a nonnulling mode for fast data acquisition. Pneumatic probes have the following advantages for testing in large low-speed wind tunnels:

1) They can accurately and simultaneously measure all three components of wake velocity and total pressure.
2) They provide time averages of data, thereby limiting the data volume and data processing time.
3) They are rugged and not easily contaminated by dirt in the tunnel circuit.

Data Reduction

In the usual procedure, the five-hole probe measures total pressure deficit and all three components of wake velocity at a large number of points, usually in excess of 10,000. Handling this data volume in a timely fashion is the most difficult aspect of the data reduction procedure. Basically, the procedure consists of two steps, a review of the data for erroneous and duplicate data sets, and the calculation of lift and drag from the final data set.

The calculation of profile drag using Eq. (4) is straightforward and only requires integration. The calculation of induced drag and lift using Eqs. (12) and (15) is more difficult since vorticity and source strength must be computed as intermediate results. These calculations require numerical differentiation of measured components V and W, which can easily lead to erroneous values of induced drag and lift if not done properly. Numerical experimentation with various schemes showed that accurate vorticity and source data could be calculated by fitting cubic splines to the measured crossflow velocities.

In order to obtain Ψ and Φ from Eqs. (10) and (11), the computational domain is extended with uniform grid spacing from the wake survey region to the walls of the wind tunnel. Where necessary, fillets in the corners of the test section are neglected. Values of axial vorticity and source strength are prescribed throughout the computational domain, which are in general nonzero in the wake survey region and zero outside. A fast Poisson solver of the FISHPAK library[17] provides solutions for Ψ and Φ. Since the total number of grid points necessary for the calculation frequently exceeds 200,000, the use of a supercomputer is required for this phase of the data

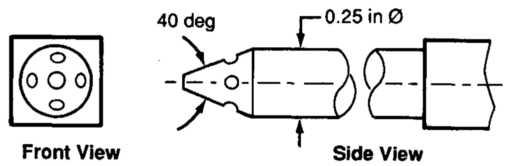

Fig. 2 Five-hole probe geometry.

reduction. Software for this purpose has been developed at Boeing.

Standard correction methods[18] are applied to lift and drag obtained from wake surveys to account for the effects of wind-tunnel walls. The effect of model support struts is accounted for by including part of the model support wake during wake surveys.

Wake Survey Test Results

Three tests are described ranging in complexity from measurements behind a simple wing to a wing-body-nacelle combination in high-lift configuration. All tests used basically the same data acquisition system and data reduction procedure, but different hardware.

High-Lift Test of Transport Aircraft

A large half-model of a twin engine transport was tested at Mach 0.22 and 1.4 million chord Reynolds number in the Boeing Transonic Wind Tunnel. The tunnel features an 8- by 12-ft test section with slotted walls. The wing was in high-lift configuration with takeoff flaps deployed. The model had a half-span of 52 in. and was installed vertically above a horizontal splitter plate. Two different engine simulations were employed including a flow-through nacelle and a turbopowered simulator (TPS). The purpose of this experiment was to determine the feasibility of making quantitative wake surveys using models of realistic high-lift configurations.

Wake surveys were conducted in a plane two mean aerodynamic chord lengths (24 in.) downstream of the inboard wing trailing edge which was as far downstream as test section and data acquisition hardware permitted. The boundaries of the wake survey region (Fig. 3) were chosen to capture wing and nacelle wakes, but did not include the wake behind the fuselage.

Wake surveys are time consuming since a large number of data points must be taken to adequately describe the wake. In this case measurements had to be performed at about 15,000 wake points. In order to complete a wake survey within a reasonable time of about 2 h, data were recorded while the probe traversed at a fixed speed. Preliminary investigations in which the traversing speed was varied showed that this mode of testing produced accurate data up to a probe speed of 1 in./s.

Measured velocities of the crossflow perpendicular to the tunnel axis were converted into axial vorticity as described above. Such vorticity data together with the measured total pressure deficit provides much insight into the structure of wing wakes (Fig. 4). The wake flows are shown in airplane view with the wingtip vortex of the right wing on the right side of the plots. The nacelle region of the TPS powered model is visible on the left side of each plot.

The vorticity data in the wake were used to calculate wing spanload as described in Ref. 19. The result is shown in Fig. 5 together with inviscid theoretical predictions of the panel code PANAIR.[20] These theoretical data represent a 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 sideforces, which in the wake survey data, could not be distinguished from lift.

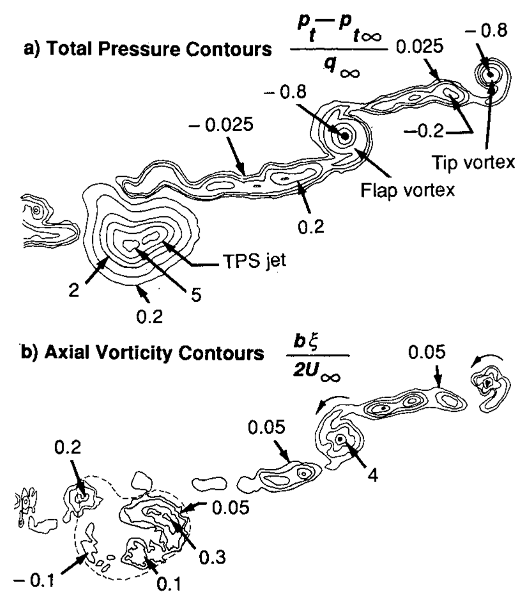

Fig. 4 Wake flow data of transport high-lift model with turbo-powered simulator (TPS) nacelles.

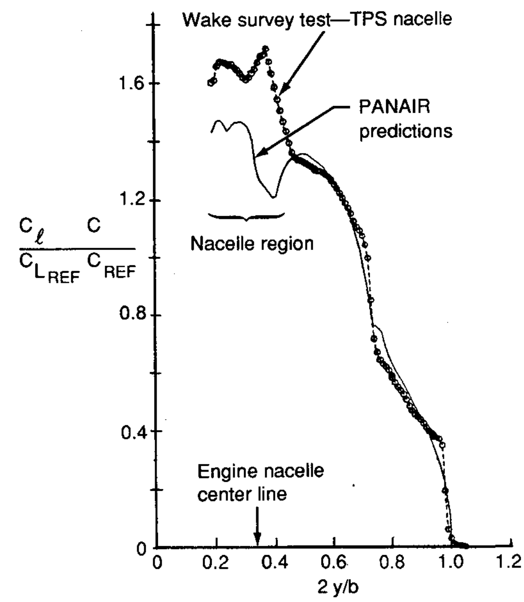

Fig. 5 Spanwise wing loads of transport high-lift model from wake survey and PANAIR code predictions.

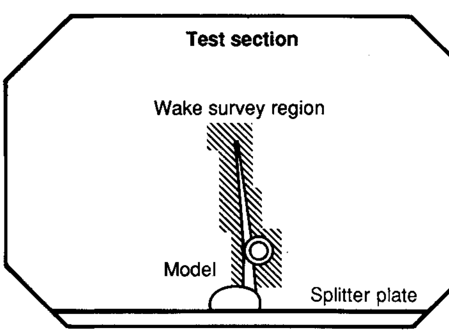

Fig. 3 Example of wake survey region.

Simple Wing Study

The main objective of this test was to learn more about the accuracy and measurement repeatability of quantitative wake surveys.[21] In this test, the wake was mapped behind a simple rectangular wing model which had a span of 6 ft and an untwisted NACA 0016 airfoil section. The test was conducted at the University of Washington Aeronautical Laboratory in an 8- by 12-ft low-speed wind tunnel. All measurements were taken at 0.18 Mach number and 1.27 million chord Reynolds number. The model was installed horizontally at the center of the test section. It was supported by a floor-mounted strut which in turn was mounted on an external balance located below the wind tunnel (Fig. 6).

Wake surveys were conducted one chord length behind the wing trailing edge and at several angles of attack below stall. A very important purpose of this and other wake tests had

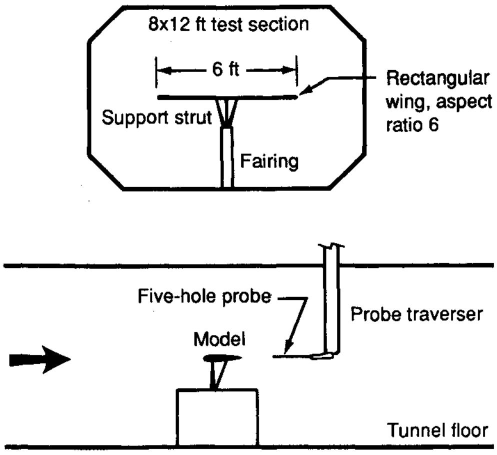

Fig. 6 Simple wing model in the University of Washington low-speed wind tunnel.

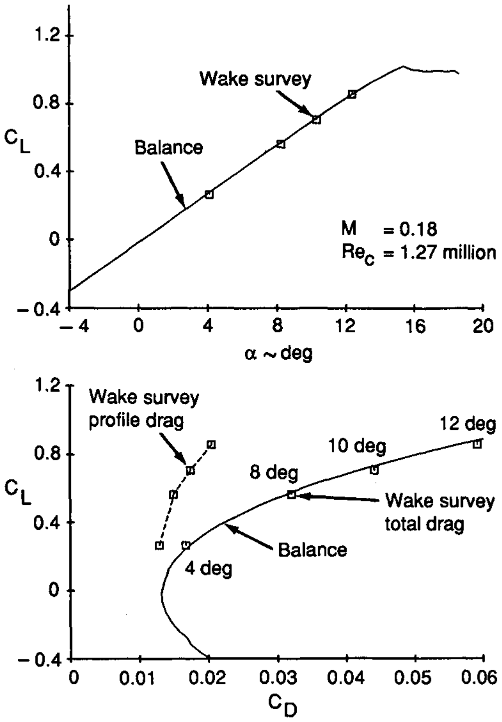

Fig. 7 Lift and drag of simple wing from wake surveys and balance.

been to verify that the planned quantitative wake survey would indeed capture the wake. This was done by applying the wake imaging technique[1] which displays total pressure contours measured by the center hole of the five-hole probe on-line. Since viscous wakes can be seen as regions of total pressure loss, the regions in which wakes have to be surveyed can easily be identified.

Lift curve and drag polar obtained from wake surveys are compared in Fig. 7 with corresponding balance data measured during this test. Wake and balance data were recorded at the same test conditions defined by the quoted angles of attack, Mach number, and Reynolds number. After the test, both types of data were corrected for wind-tunnel wall effects in exactly the same way. Figure 7 also shows the variation of profile drag with lift measured during wake surveys. Excellent agreement of wake and balance data is shown in this figure, providing proof of the high measurement accuracy that can be achieved in quantitative wake surveys.

For practical applications, the ability of a wake survey technique to repeat the measurements with very little data scatter is as important as a good absolute measurement accuracy. Table 1 contains tabulated data for lift and drag components

Table 1 Repeatability of wake lift and drag measurements at α = 8.2 deg

Wake survey	C_L	C_D	C_{Dp}	C_{Di}
1	0.5668	0.0323	0.0155	0.0168
2	0.5653	0.0319	0.0148	0.0171
3	0.5651	0.0321	0.0150	0.0171

Table 2 Repeatability of balance lift and drag measurements at α = 8.2 deg

Balance run	C_L	C_D
1	0.5738	0.0319
2	0.5722	0.0318
3	0.5722	0.0319
4	0.5709	0.0319

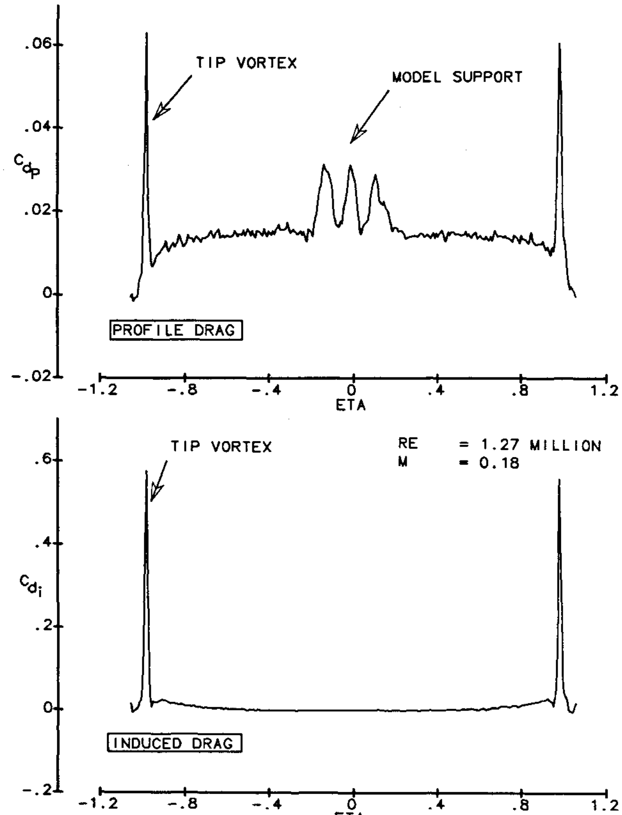

Fig. 8 Spanwise distributions of profile drag and induced drag integrand for simple wing at α = 8 deg.

measured in three different wake surveys at the same angle of attack and at the same wake location. These are true repeat runs conducted several days apart. All wake data repeated very well, particularly lift, total drag, and induced drag. Profile drag scatter is slightly higher than the scatter in the other data. For comparison, Table 2 contains repeat balance data at the same wind-tunnel test conditions.

During this wind-tunnel experiment, vortex generators were mounted on the model in order to determine the accuracy of wake surveys in measuring drag increments due to configuration changes. Measured total wake drag increments were found to be within one drag count of balance drag increments. Note that this difference is the same as the scatter in the balance drag data shown in Table 2. These results not only demonstrated the excellent accuracy of measuring wake drag increments, but also shows that wake surveys furnish the in-

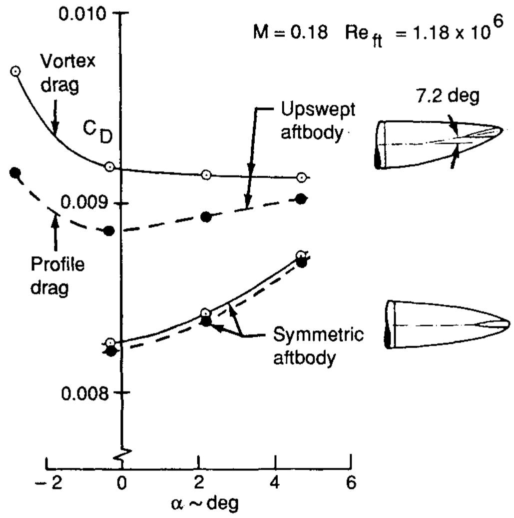

Fig. 9 Drag components of symmetric and upswept aft-body configurations.

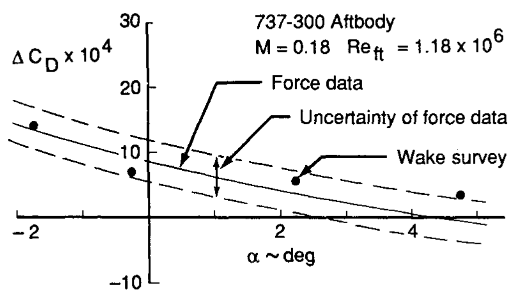

Fig. 10 Upsweep drag from balance and wake surveys.

crements of profile drag and induced drag associated with the addition of vortex generators.

Spanwise distributions of profile drag and induced drag measured in the wake of this simple rectangular wing are shown in Fig. 8. Here the spanwise value of induced drag is the integrand of the induced drag integral of Eq. (12). Notice that this quantity differs from the usual definition of spanwise induced drag calculated as the product of wing section lift and induced angle of attack.

Aft-Body Drag Tests

Wake surveys were conducted with various fuselage models of transport airplanes in order to improve our understanding of aft-body flowfields and the drag associated with them. Contrary to most military transports, civil transports feature moderate aft-body upsweep with a correspondingly smaller contribution to drag. The vortices shed from such aft-bodies are relatively weak, but their associated drag must nevertheless be understood when seeking opportunities for airplane drag reduction.

Aft-body drag experiments were carried out in the Boeing Research Wind Tunnel in Seattle at 0.18 Mach number and 1.18 million Reynolds number per foot. In all tests, the fuselage was supported by wing stubs extending through the tunnel side walls. The wingtips, in turn, were mounted on an external balance, situated below the test section. This allowed a comparison of wake survey drag measurements with balance drag.

Parametric studies investigating the effect of aft-body length and upsweep angle on fuselage drag provided quantitative data for vortex drag and profile drag as functions of angle of attack.[22] As shown in the example of Fig. 9, vortex drag of upswept and symmetric aft-bodies of civil transports can be measured in wake surveys with very little data scatter even though aft-body vortex drag is indeed very small.

Wake measurements of upsweep drag of a Boeing 737-300 airplane model are compared in Fig. 10 with balance data. This kind of drag is defined as the difference in drag between symmetric and upswept aft-bodies at the same test condition. As seen, wake drag is well within the uncertainty band of the force measurements providing further demonstration for the accuracy of three-dimensional wake measurements.

Conclusions

This article describes the wake survey methodology developed at Boeing for the purpose of measuring the components of drag of low speed, high-lift configurations. Important elements of this technique including mechanical probe traverser and pneumatic probe design, refinement of the underlying theory, and data reduction procedures are still under development at the present time. However, the technique has already been successfully applied in several wind-tunnel tests as shown in this article. The following valuable features of this measuring technique should be noted:

1) The wake survey technique provides separate measurements of induced drag, profile drag, and lift.

2) Measurement accuracy and data repeatability are comparable to balance measurements, even though lift and drag data are the composites of a large number of individual measurements.

3) Small increments in individual components of drag due to minor configuration changes can be measured accurately.

4) Spanwise distributions of lift can be obtained. This is of value in high-lift aerodynamics since the small flap sizes of most high-lift models make it extremely difficult to measure spanlift data using surface pressure taps. However, all spanwise wing data measured in wake surveys should be interpreted with caution since they are usually distorted to some degree by wake roll-up, and hence are influenced by practical limitations on the location of the plane in which the survey is conducted.

5) Wake surveys provide spanwise distributions of profile drag and induced drag, which are of value in diagnosing the effects of local changes to the configuration geometry.

6) During each wake survey a large number of velocity and pressure data are recorded which can serve as validation data for CFD codes in addition to providing lift and drag data.

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References

[1]Crowder, J. P., "Quick and Easy Flow Field Surveys," *Astronautics and Aeronautics*, Vol. 45, Oct. 1980, pp. 38, 39.

[2]Maskell, E. C., "Progress Towards a Method for the Measurement of the Components of the Drag of a Wing of Finite Span," Royal Aircraft Establishment, TR 72232, UK, Dec. 1972.

[3]Schlichting, H., "Determination of Profile Drag," *Boundary-Layer Theory*, 6th ed., McGraw Hill, New York, 1968, Chap. 25, pp. 708–711.

[4]Betz, A., "Ein Verfahren zur direkten Ermittlung des Profilwiderstandes," *Zeitschrift für Flugtechnik und Motorluftschiffahrt*, Vol. 16, 1925, pp. 42–44.

[5]Wu, J. C., Hackett, J. E., and Lilley, D. E., "A Generalized Wake-Integral Approach for Drag Determination in Three-Dimensional Flows," AIAA Paper 79-0279, Jan. 1979.

[6]Hackett, J. E., and Wu, J. C., "Drag Determination and Analysis from Three-Dimensional Wake Measurements," International Council of the Aeronautical Sciences Paper 82-644, Aug. 1982.

[7]Hackett, J. E., and Sugavanam, A., "Evaluation of a Complete Wake Integral for the Drag of a Car-Like Shape," Society of Automotive Engineers Paper 840577, Feb. 1984.

[8]Onorato, M., Costelli, A. F., and Garrone, A., "Drag Measure-

ment Through Wake Analysis," Society of Automotive Engineers Paper 840302, Feb. 1984.

[9]Chometon, F., and Laurent, J., "Study of Three-Dimensional Separated Flows, Relation Between Induced Drag and Vortex Drag," *European Journal of Mechanics, B/Fluids*, Vol. 9, No. 5, 1990, pp. 437–455.

[10]Weston, R. P., "Refinement of a Method for Determining the Induced and Profile Drag of a Finite Wing from Detailed Wake Measurements," Ph.D. Dissertation, Univ. of Florida, Gainesville, FL, March 1981.

[11]Batchelor, G. K., "Axial Flow in Trailing Line Vortices," *Journal of Fluid Mechanics*, Vol. 20, Pt. 4, 1964, pp. 645–653.

[12]El-Ramly, Z., Rainbird, W. J., and Earl, D. G., "Wind Tunnel Measurements of Rolling Moment in a Swept-Wing Vortex Wake," *Journal of Aircraft*, Vol. 13, No. 12, 1976, pp. 962–967.

[13]El-Ramly, Z. M., and Rainbird, W. J., "Effect of Simulated Jet Engines on the Flowfield Behind a Swept-Back Wing," *Journal of Aircraft*, Vol. 14, No. 4, 1977, pp. 343–349.

[14]El-Ramly, Z. M., and Rainbird, W. J., "Computer-Controlled System for the Investigation of the Flow Behind Wings," *Journal of Aircraft*, Vol. 14, No. 7, 1977, pp. 668–674.

[15]El-Ramly, Z. M., and Rainbird, W. J., "Flow Survey of the Vortex Wake Behind Wings," *Journal of Aircraft*, Vol. 14, No. 11, 1977, pp. 1102–1108.

[16]Van Dam, C. P., Nikfetrat, K., Chang, I. C., and Vijgen, P. M. H. W., "Drag Calculations of Wings Using Euler Methods," AIAA Paper 91-0338, Jan. 1991.

[17]Schwarztrauber, P. N., and Sweet, R. A., "Efficient Fortran Subprograms for the Solution of Separable Elliptic Partial Differential Equations," *Association of Computing Machinery Transactions of Mathematical Software*, Vol. 5, No. 3, 1979, pp. 352–364.

[18]Rae, W. H., Jr., and Pope, A., *Low Speed Wind Tunnel Testing*, 2nd ed, Wiley, New York, 1984.

[19]Brune, G. W., and Hallstaff, T. H., "Wing Span Loads of Complex High-Lift Systems from Wake Measurements," *Journal of Aircraft*, Vol. 22, No. 9, 1985, pp. 831, 832.

[20]Tinoco, E. N., "CFD Applications to Complex Configurations: A Survey," in *Applied Computational Aerodynamics*, Vol. 125, Progress in Astronautics and Aeronautics, AIAA, New York, 1990, pp. 559–584.

[21]Brune, G. W., and Bogataj, P. W., "Induced Drag of a Simple Wing from Wake Measurements," Society of Automotive Engineers Paper 901934, Oct. 1990.

[22]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, March 1984.