Conclusions

The present theory incorporating rollup and swirl in the slipstream is based on a realistic equilibrium model. It does not suffer from high pressure in the slipstream. In the actuator limit, $J = 0$, its values of thrust and power coefficients and of the efficiency approach the established values of actuator disk theory.

The actuator disk must be considered as a true limiting case of the propeller.

In the example of Hanson's eight-bladed propfan, the rigid-sheet methods yielded values for the efficiency that are 3–3.5% above the experimental value; the present theory yields an efficiency that is only 1.5% below the measured value. This result is interpreted as a support for the amended theory incorporating rollup and swirl.

References

[1]Theodorsen, T., *Theory of Propellers*, McGraw–Hill, New York, 1948.

[2]Schouten, G., "Theodorsen's Ideal Propeller Performance with Ambient Pressure in the Slipstream," *Journal of Aircraft*, Vol. 30, No. 3, 1993, pp. 417–419.

[3]Schouten, G., "Static Pressure in the Slipstream of a Propeller," *Journal of Aircraft*, Vol. 19, No. 3, 1982, pp. 251–252.

[4]Ribner, H. S., "Neglect of Wake Rollup in Theodorsen's Theory of Propellers," *Journal of Aircraft*, Vol. 34, No. 6, 1997, pp. 814–816.

[5]Hanson, D. B., "Compressible Lifting Surface Theory for Propeller Performance Calculation," *Journal of Aircraft*, Vol. 22, No. 1, 1985, pp. 19–27.

[6]Sparenberg, J. A., "On the Linear Theory of an Actuator Disk in a Viscous Fluid," *Journal of Ship Research*, Vol. 18, No. 1, 1974, pp. 16–21.

[7]van Holten, T., "Concentrator Systems for Wind Energy, with Emphasis on Tipvanes," *Wind Engineering*, Vol. 5, No. 1, 1981, pp. 29–45.

Equivalence Between Sideslip and Roll in Wind-Tunnel Model Testing

S. Tavoularis*
University of Ottawa, Ottawa, Ontario, Canada K1N 6N5

Introduction

ASYMMETRIC orientations of fighter aircraft with respect to the direction of motion occur frequently during maneuvering; similar situations may arise during aerobatic performances, as well as when aircraft are subjected to strong crosswinds. The aerodynamic and aeroelastic performance of an aircraft and its components depends strongly on its orientation, and substantial tests have been performed to identify, in particular, the effects of sideslip. The effect of steady roll, which is equally important, has not been as well documented, although the rolling stability of aircraft has been a main issue of concern. Most of the quantitative information on aircraft aerodynamics has been collected through wind-tunnel testing, in which an aircraft model is mounted on a sting that can be rotated by one or more angles. It is obvious from economic and time considerations that the design of the mounting system should be as simple as possible and that the number of necessary tests should be minimal. Therefore, any procedure that may facilitate the design of model mounting systems or the extraction of aerodynamic information at one aircraft orientation from that at a more convenient one would be highly desirable. Although it is well known[1] that any orientation of an aircraft with respect to the direction of the wind (freestream) can be uniquely specified by the values of two angles, the angle of attack and the sideslip angle, and although a general compilation of aerodynamic axes systems and geometric relationships permitting the transfer from one system to another is available,[2] the equivalence between orientations obtained by a combination of pitching–yawing and by a combination of pitching–rolling has not been specifically addressed in the available literature. The purpose of this Note is to derive such a relationship and to clarify its usefulness in wind-tunnel testing.

Received 11 May 1999; accepted for publication 19 May 1999. Copyright © 1999 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved.

*Professor, Department of Mechanical Engineering. Member AIAA.

Derivation of Equivalent Angle Relationships

Consider the aircraft shown schematically in Fig. 1. The body axes, x, y, and z, are Cartesian axes defined such that x is the longitudinal axis of the aircraft, y is the lateral axis, usually in the plane of the wings, and z is in the plane of symmetry of the aircraft and perpendicular to the other two. Let $\boldsymbol{V}$ be the velocity vector of the freestream and u, v, and w be its projections on the x, y, and z axes, respectively. The angle of attack α is defined as the angle between the projection of the wind axis on the x–z plane and the x axis, such that

$$a = \tan^{-1}(w/u) \tag{1}$$

The sideslip angle is defined as the angle between the wind axis and its projection on the x–z plane, such that

$$\beta = \sin^{-1}(v/V) \tag{2}$$

Then, the total or complex angle of attack α^* is defined as the angle between the wind axis and the x axis, such that

$$a^* = \cos^{-1}(u/V) \tag{3}$$

Let x_0, y_0, and z_0 (Fig. 1) be the directions of the body axes that correspond to an orientation of the aircraft such that the aircraft axis x_0 is aligned with the wind direction. Any arbitrary orientation of the aircraft with respect to the wind direction may be achieved by first rotating the aircraft about the y_0 axis, by an angle of attack α, and then about the z_0 axis, by a sideslip angle β. The same relative orientation may be achieved by first rotating the aircraft about the y_0 axis by an angle of attack α^*, and then about the x axis by a roll angle φ, which is, thus, defined as the angle between the y axis and the y_0 axis. These two orientations are equivalent because the corresponding body axes, although not parallel to each other, form the same angles with the vector $\boldsymbol{V}$ and, therefore, result in equal corresponding components of the wind vector on the body axes. The two sets of body axes can be made parallel by a rigid-body rotation of the latter system (namely, the one obtained by a set of α^*–φ rotations) about the freestream direction by an angle φ.

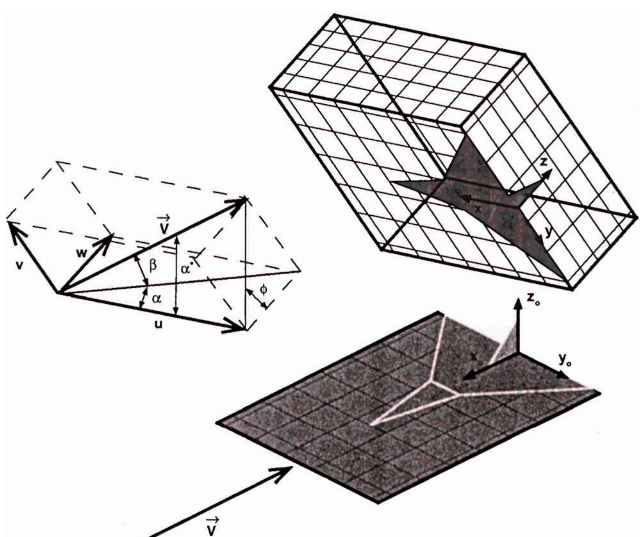

Fig. 1 Two aircraft orientations and the components of the freestream velocity vector (wind) with respect to the body-fixed coordinate axes.

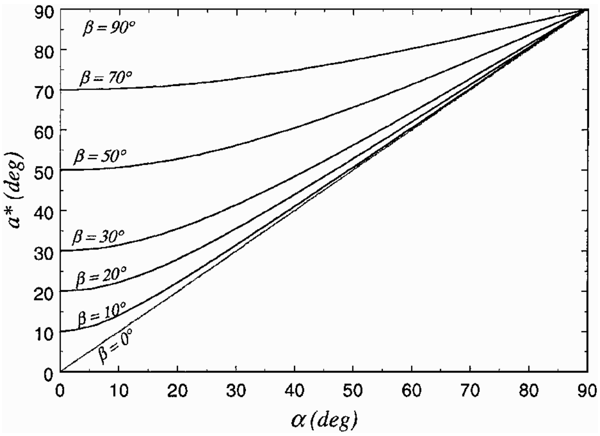

Fig. 2 Equivalent angles of attack in orientations with pure sideslip and pure roll.

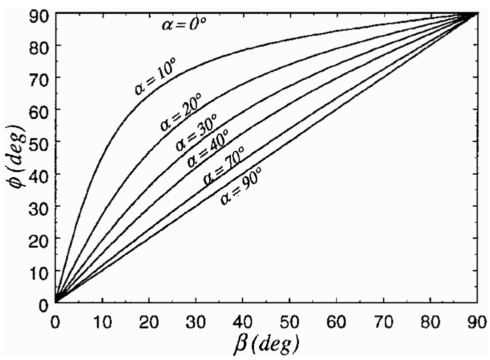

Fig. 3 Equivalent roll and sideslip angles.

From simple geometric considerations (Fig. 1), one may derive the expressions

$$u = V \cos\beta \cos\alpha \tag{4}$$

$$w = V \cos\beta \sin\alpha \tag{5}$$

$$v = V \sin a^* \sin\varphi \tag{6}$$

$$w = V \sin a^* \cos\varphi \tag{7}$$

From Eqs. (3) and (4), one gets a relationship between the equivalent angles of attack as

$$a^* = \cos^{-1}(\cos\beta \cos\alpha) \tag{8}$$

Further equating the ratios v/w obtained by combining Eqs. (2) and (5) and Eqs. (6) and (7), one gets a relationship between the equivalent roll and sideslip angles as

$$\varphi = \tan^{-1}(\tan\beta / \sin\alpha) \tag{9}$$

The equivalent angle α^* has been plotted vs α for different values of β in Fig. 2. It is obvious that, when $\beta = 0$, then $\alpha = a^*$, whereas when $\alpha = 0$, then $\alpha^* = \beta$. For small β (typically, for $\beta < 5$ deg), $\alpha \approx \alpha^*$, but, otherwise, there is a significant difference between α and α^*. The equivalent φ has been plotted vs β for different values of α in Fig. 3. Clearly, $\varphi = 90$ deg, when $\alpha = 0$, and $\varphi = \beta$, when $\alpha = 90$ deg. For small β (typically, for $\beta < 5$ deg), $\varphi \approx \beta / \sin\alpha$, for example, $\varphi \approx \frac{1}{2}\beta$, for $\alpha = 30$ deg.

Conclusions

The described method permits the conversion of wind-tunnel results obtained by angle-of-attack/sideslip-angle combinations into equivalent roll results. If applied at an early stage of planning, the same approach provides guidance for the design of the simplest model mounting system that would permit the model orientation within the desired range.

Acknowledgment

The author acknowledges the financial support of the Institute for Aerospace Research, National Research Council of Canada, and the useful discussions with B. H. K. Lee and X. Z. Huang.

References

[1]Etkin, B., *Dynamics of Atmospheric Flight*, Wiley, New York, 1972, Chap. 4.3, p. 114.

[2]Wright, J., *A Compilation of Aerodynamic Nomenclature and Axes Systems*, United States Naval Ordnance Lab., NOLR 1241, White Oak, Silver Spring, MD, 1962, pp. 1–93.

Acceleration Effect on the Stanton Number for Castings of Ice-Roughened Surfaces

Nihad Dukhan,* K. C. Masiulaniec,†
and Kenneth J. De Witt‡
University of Toledo, Toledo, Ohio 43606
and
G. James Van Fossen Jr.§
NASA John H. Glenn Research Center at Lewis Field, Cleveland, Ohio 44135

Introduction

A PREVIOUS study[1] provided fundamental information on the effect of surface roughness, due to ice accretion, on the surface rate of heat transfer for parallel flow over aluminum castings of stochastically accreted ice. The roughness enhanced the heat transfer rate and lowered the Reynolds number for the onset of transition to turbulent flow as compared to the smooth model case. The Stanton numbers were higher than those obtained with the uniform roughness elements of other studies.[2,3] The current study was conducted to provide characteristics of the convective heat transfer from stochastically accreted ice-roughened surfaces, described in Ref. 1, in accelerated flows. These data are needed for the effective sizing and design of in-flight de-icing systems.

Few previous studies have included the effect of acceleration on the rate of heat transfer from rough surfaces. Coleman[4] stated that flow acceleration increased the heat transfer rate in the fully rough regime, and Poinsatte et al.[5] reported that varying the angle of attack for an artificially roughened airfoil caused heat transfer to increase over the 0-deg case.

Heat transfer data for the smooth flat plate model and for each of the seven roughness models described in Ref. 1 were collected for the approach velocities of $u_\infty = 9.4, 20.7$, and 32.6 m/s at inclination angles of $\theta = 5$, 14, 23, and 41 deg. This Note presents complete results for the smooth model at $u_\infty = 32.6$ m/s and roughness model

Presented as Paper 96-0867 at the AIAA 34th Aerospace Sciences Meeting, Reno, NV, 15–19 January 1996; received 7 April 1998; revision received 22 March 1999; accepted for publication 23 March 1999. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

*Graduate Student, Department of Mechanical, Industrial and Manufacturing Engineering; currently Senior Engineer, RELTEC Corporation, 4350 Weaver Parkway, Warrenville, IL 60555-3930.

†Associate Professor, Department of Mechanical, Industrial and Manufacturing Engineering.

‡Professor, Department of Chemical Engineering.

§Senior Research Scientist, Turbomachinery and Propulsion Systems Division.