Technical Notes

TECHNICAL 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).

Low Reynolds Number Effects on Subsonic Compressibility Corrections

Ajay P. Kothari* and John D. Anderson Jr.†
University of Maryland, College Park, Maryland

Introduction

IN recent years, interest in low Reynolds number aerodynamics has grown, driven in part by the design of new remotely piloted vehicles (RPV's) for long endurance missions. These RPV's are usually small and therefore fly at relatively low Reynolds numbers. A specific problem in RPV design has been the lack of a substantial airfoil data base at low Reynolds numbers ($Re \approx 100{,}000$ to 300,000 based on chord length). To rectify this problem, an extensive experimental program on low Reynolds number effects on airfoils and wings has been carried out by Mueller and Batill,[1] Arena and Mueller,[2] and Pohlen and Mueller[3] and more recently by Marchman and Abtahi.[4] Indeed, a comprehensive compilation of recent low Reynolds number work is given in Ref. 5. As a complement to this experimental effort, Ref. 6 describes the application of computational fluid dynamics to low Reynolds number flows over airfoils; specifically, Ref. 6 details a complete two-dimensional solution of the compressible Navier-Stokes equations for the flows over Miley and Wortmann airfoils—airfoils designed for low Reynolds number applications. The numerical technique employed in Ref. 6 is the time-dependent implicit finite-difference method of MacCormack.[7] The turbulence model of Baldwin and Lomax[8] is employed to simulate transition and turbulent flow.

Although many previous RPV's have been designed for flight at very low speeds (essentially incompressible flow conditions), new generations of RVP's are being considered for high subsonic speeds (where compressibility effects can be important). The standard compressibility corrections, such as the well-known Prandtl-Glauert rule, are based on inviscid flow theory.[9,10] No work has been done to examine the low Reynolds number effect on these compressibility corrections. In the present Note, a numerical experiment is carried out which demonstrates that the highly viscous effects associated with low Reynolds number flows have an important impact on subsonic compressibility corrections.

In particular, the compressible Navier-Stokes code described in Ref. 6 is used to calculate the flow over a Wortmann FX 63-137 airfoil at $M_\infty = 0.5$, 0.4, and 0.3. (As in the case of many other compressible flow computer codes, stable solutions could not be obtained at very low Mach numbers of $M_\infty = 0.2$ or less.) The calculated lift coefficients are normalized by the calculated lift coefficient at $M = 0.5$, and they are plotted vs the Mach number in Fig. 1. The present viscous results are compared with the standard Prandtl-Glauert rule, which states that

$$\frac{C_L}{(C_L)_{M_\infty=0.5}} = \sqrt{\frac{1-(0.5)^2}{1-M_\infty{}^2}}$$

In Fig. 1, the viscous results (solid circles) show a major deviation away from the Prandtl-Glauert rule (open squares). Also, the viscous results, when extrapolated to low Mach numbers, agree very well with the experimental data of Bastedo and Mueller,[11] shown as the solid triangle in Fig. 1. Moreover, at low Reynolds numbers, these results demonstrate that C_L is almost *independent* of M_∞, at least up to $M_\infty = 0.5$. The practical implication here is that some incompressible data for RVP's may hold to Mach numbers as high as 0.5 without requiring any compressibility correction.

The variation of turbulent viscosity as a function of the *x-y* coordinates in the flowfield around the airfoil are shown in the "carpet" plots of Figs. 2a, 2b, and 2c. In these figures, the turbulent viscosity is plotted as the vertical coordinate perpendicular to the *x-y* plane, and the whole picture is rotated slightly in perspective. As described in detail in Ref. 6, the Baldwin-Lomax turbulence model is based on the local vorticity in the flow and, although there is no direct correlation between the turbulence model and transition, this model does appear to simulate transition in a crude sense for the present low Reynolds number cases. Indeed, Ref. 6 contains good comparisons between experiment and the present calculations for transition. The results in Figs. 2a, 2b, and 2c are for $M_\infty = 0.5$, 0.4, and 0.3, respectively, and show a regular progression of the transition region toward the leading edge as M_∞ is reduced. This is consistent with the general rule that laminar stability increases with Mach number. Figures 2a–c are included here as an example of compressibility effects on

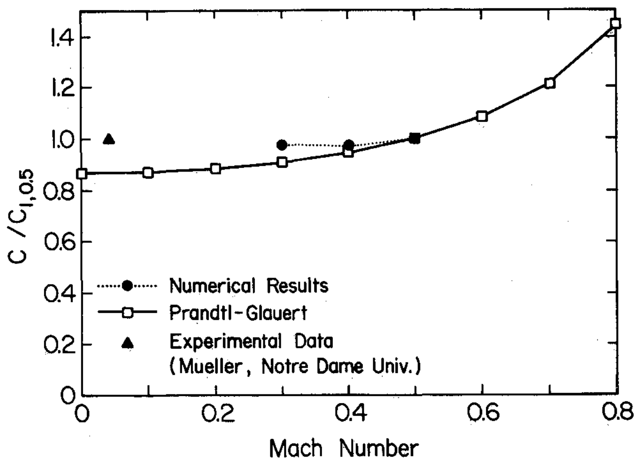

Fig. 1 Plot of Prandtl-Glauert rule vs numerical results.

Received Nov. 20, 1986; revision received March 13, 1987.

*Research Engineer, Department of Aerospace Engineering. Member AIAA.

†Professor, Department of Aerospace Engineering; presently on sabbatical as the Charles Lindbergh Professor, National Air and Space Museum, Smithsonian Institution. Fellow AIAA.

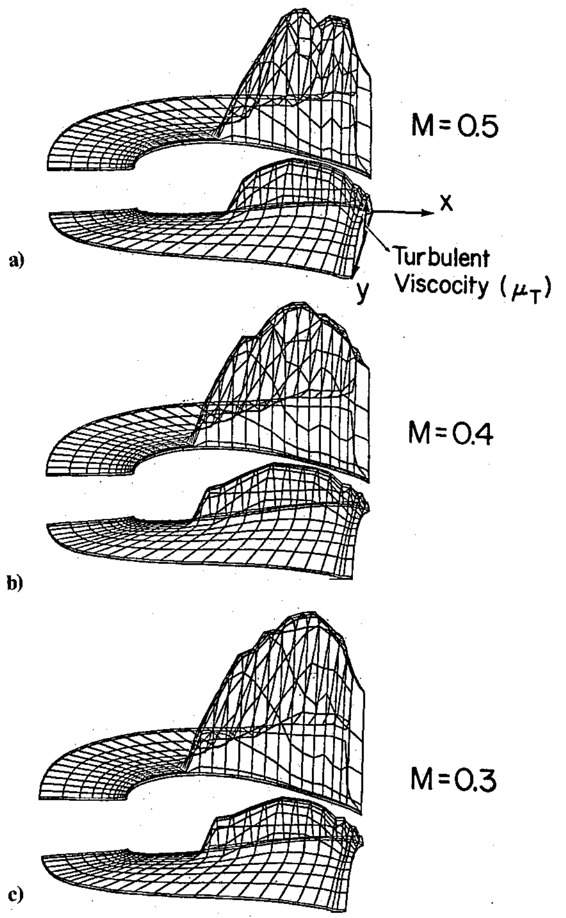

Fig. 2 Three-dimensional plot of turbulent viscosity; $Re = 100,000$, angle of attack = 7 deg.

the regions of turbulence in these low Reynolds number flows and illustrate no unexpected trends.

Conclusion

In summary, the present Note describes the first work to assess, albeit in an elementary sense, how low Reynolds numbers may affect the standard compressibility corrections for airfoil properties. Our purpose here is to indicate that such low Reynolds number effects may be important. Moreover, it appears that the highly viscous effects result in a relatively constant C_L, at least up to $M_\infty = 0.5$.

Acknowledgments

Acknowledgment is given to the Office of Naval Research, which supported this work under Grant N00014-85-K-0246, with Robert Whitehead, T.C. Tai, and Spiro Lekoudis as monitors.

References

[1]Mueller, T.J. and Batill, S.M., "Experimental Studies of the Laminar Separation Bubble on a Two-Dimensional Airfoil at Low Reynolds Numbers," AIAA Paper 80-1440, July 1980.

[2]Arena, A.V. and Mueller, T.J., "Laminar Separation, Transition, and Turbulent Reattachment Near the Leading Edge of Airfoils," *AIAA Journal*, Vol. 18, July 1980, pp. 747–753.

[3]Pohlen, L.J. and Mueller, T.J., "Boundary Layer Characteristics of the Miley Airfoil at Low Reynolds Numbers," *Journal of Aircraft*, Vol. 21, Sept. 1984, pp. 658–664.

[4]Marchman, J.F. III and Abtahi, A.A., "Aerodynamics of an Aspect Ratio 8 Wing at Low Reynolds Numbers," *Journal of Aircraft*, Vol. 22, July 1985, pp. 628–634.

[5]*Proceedings of the Conference on Low Reynolds Number Airfoil Aerodynamics*, edited by Thomas Mueller, Notre Dame University, Notre Dame, IN, June 17–18, 1985.

[6]Kothari, P. and Anderson, J.D. Jr., "Flows Over Low Reynolds Number Airfoils—Compressible Navier-Stokes Numerical Solutions," AIAA Paper 85-0107, Jan. 1985.

[7]MacCormack, R.W., "A Numerical Method for Solving the Equations of Compressible Flow," AIAA Paper 81-0110, 1981.

[8]Baldwin, B.S. and Lomax, H., "Thin Layer Approximation and Algebraic Model for Separated Turbulent Flows," AIAA Paper 78-257, Jan. 1978.

[9]Anderson, J.D. Jr., *Fundamentals of Aerodynamics*, McGraw-Hill, New York, 1984.

[10]Anderson, J.D. Jr., *Modern Compressible Flow: With Historical Perspective*, McGraw-Hill, New York, 1982.

[11]Bastedo, W.G. and Mueller, T.J., "Spanwise Variation of Laminar Separation Bubbles on Wings at Low Reynolds Numbers," *Journal of Aircraft*, Vol. 23, Sept. 1986, pp. 687–694.

Application of a Panel Code to Unsteady Wing-Propeller Interference

A.A. Rangwalla* and L.N. Wilson†
Iowa State University, Ames, Iowa

Introduction

THE present work deals with the prediction of unsteady, incompressible, potential flow using a low-order paneling method. The method used is an extension of VSAERO, developed by Maskew.[1]

Paneling methods have been used by others to predict unsteady lifting flows. A short representative review of the methods and problems solved are given in Refs. 2–10. One of the first attempts at predicting three-dimensional, unsteady lifting flows is reported in Ref. 3. Here, the complete nonlinear problem was solved; that is, the small perturbation approximation was not made. However, no examples of unsteady, three-dimensional wake structures were presented. In Ref. 9, a free wake analysis of helicopter rotors in incompressible unsteady potential flows was presented. The methodology presented in Ref. 9 is very similar to the present one. More references by the same author can be found there.

The present approach is a nonlinear one in that the small perturbation approximation is not made. This approach has the advantage of being able to solve quite general problems such as the one that was the primary objective of this development, the unsteady interference between a two-bladed propeller and a wing. To the authors' knowledge, this problem has not been solved before.

Formulation of the General Problem

For the formulation of the problem and the calculation of the subsequent wake development, the reader is referred to Refs. 1 and 11, where greater detail is provided. It is sufficient to state that the numerical procedure consisted of solving the Laplace equation at every time step. The wing and propeller were impulsively started. The position of the propeller with respect to the wing was changed between time steps. The wake emanated from the trailing edges of the wing and propeller. This wake was convected downstream with the local velocity calculated at the corner points of the wake panels.

Received Oct. 14, 1986; revision received Jan. 31, 1987.

*Graduate Assistant; presently, Research Associate.

†Professor and Chairman, Aerospace Engineering Department. Associate Fellow AIAA.