References

Abu-Ghannam, B. J., and Shaw, R., 1980, "Natural Transition of Boundary Layers—The Effects of Turbulence, Pressure Gradient, and Flow History," *Journal of Mechanical Engineering Science*, Vol. 22, No. 5, pp. 213–228.

Ball, C. L., Reid, L., and Schmidt, J. F., 1983, "End-Wall Boundary Layer Measurements in a Two Stage Fan," NASA TM 83409.

Coles, D. E., 1956, "The Law of the Wake in the Turbulent Boundary Layer," *Journal of Fluid Mechanics*, Vol. 1, pp. 191–226.

Crawford, M. E., and Kays, W. M., 1976, "STAN5—A Program for Numerical Computation of Two-Dimensional Internal and External Boundary Layer Flows," COSMIC Program No. LEW-13009, NASA CR-2742.

Deutsch, S., and Zierke, W. C., 1986, "The Measurement of Boundary Layers on a Compressor Blade in Cascade at High Positive Incidence Angle: Part II—Data Report," NASA Contractor Report 179492.

Deutsch, S., and Zierke, W. C., 1987, "The Measurement of Boundary Layers on a Compressor Blade in Cascade: Part 1—A Unique Experimental Facility," ASME JOURNAL OF TURBOMACHINERY, Vol. 109, pp. 520–526.

Deutsch, S., and Zierke, W. C., 1988*a*, "The Measurement of Boundary Layers on a Compressor Blade in Cascade: Part 2—Suction Surface Boundary Layers," ASME JOURNAL OF TURBOMACHINERY, Vol. 110, pp. 138–145.

Deutsch, S., and Zierke, W. C., 1988*b*, "The Measurement of Boundary Layers on a Compressor Blade in Cascade: Part 3—Pressure Surface Boundary Layers and the Near Wake," ASME JOURNAL OF TURBOMACHINERY, Vol. 110, pp. 146–152.

Falkner, V. M., and Skan, S. W., 1931, "Some Approximate Solutions of the Boundary Layer Equations," *Phil. Mag.*, Vol. 12, No. 7, pp. 865–896.

Hobbs, D. E., Wagner, J. H., Dannenhoffer, J. F., and Dring, R. P., 1982, "Experimental Investigation of Compressor Cascade Wakes," ASME Paper No. 82-GT-299.

Lakshminarayana, B., and Davino, R., 1980, "Mean Velocity and Decay Characteristics of the Guide Vane and Stator Blade Wake of an Axial Flow Compressor," ASME *Journal of Engineering for Power*, Vol. 102, pp. 50–60.

Lieblein, S., Schwenk, F. C., and Broderick, R. L., 1953, "Diffusion Factor for Estimating Losses and Limiting Blade Loadings in Axial-Flow-Compressor Blade Elements," NACA RM E53 D01.

Lieblein, S., and Roudebush, W. H., 1956, "Theoretical Loss Relations for Low-Speed Two-Dimensional-Cascade Flow," NACA TN3662.

Ludweig, H., and Tillman, W., 1949, "Untersuchungen über die Wandschubspannung in Turbulenten Reibungsschenhten," *Ing.-Arch.*, Vol. 17, pp. 288–299. (English Translation, NACA TM 1285.)

Mellor, G. L., and Wood, G. M., 1971, "An Axial Compressor End-Wall Boundary Layer Theory," ASME *Journal of Basic Engineering*, Vol. 93, Series D, No. 1, pp. 300–316.

Murlis, J., Tsai, H. M., and Bradshaw, P., 1982, "The Structure of Turbulent Boundary Layers at Low Reynolds Numbers," *Journal of Fluid Mechanics*, Vol. 122, pp. 13–56.

Sandborn, V. A., and Kline, S. J., 1961, "Flow Models in Boundary Layer Stall Inception," ASME *Journal of Basic Engineering*, Vol. 83, pp. 317–327.

Simpson, R. L., Strickland, J. H., and Barr, P. W., 1977, "Features of a Separating Turbulent Boundary Layer in the Vicinity of Separation," *Journal of Fluid Mechanics*, Vol. 79, Part 3, pp. 553–594.

Simpson, R. L., Chew, Y.-T., and Shipvaprasad, B. G., 1981, "The Structure of a Separating Turbulent Boundary Layer: Part 1—Mean Flow and Reynolds Stresses," *Journal of Fluid Mechanics*, Vol. 113, pp. 23–51.

Smits, A. J., Matheson, N., and Joubert, P. N., 1983, "Low Reynolds Number Turbulent Boundary Layers in Zero and Favorable Pressure Gradients," *Journal of Ship Research*, Vol. 27, No. 3, pp. 147–157.

DISCUSSION

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The authors have obtained a most impressive amount of data in the four papers culminating in this one. May one ask if the measurements could be made more accessible: The presentation in Figs. 4, 5, 7, and 8 is too compact for the results to be very useful.

The main reason for writing this discussion is, at risk of being repetitive, to draw attention to the need for caution. This is based on our own measurements (Dong and Cumpsty, 1989). By introducing moving wakes into the two-dimensional flow in a cascade of supercritical (controlled-diffusion) type blades, we were able to see very substantial alterations in the suction and pressure surface boundary layers. The effects were most pronounced on the suction surface, since this boundary layer was dominated by a separation bubble in the absence of wakes or high free-stream turbulence. The wakes initiated turbulence before the separation point and temporarily prevented separation; after a wake had passed the flow reverted to laminar and a separation occurred. After the turbulent spot there was a calmed region, in which transition was delayed, and the net effect of the wakes (and of high free-stream turbulence) was to delay the completion of transition to a position further downstream. The transition, and therefore, the subsequent boundary layer development, depend on the size and frequency of the wakes and the whole process is an unsteady one.

Our measurements, therefore, bring us to offer a caveat to the assumption that the measurements by Zierke and Deutsch will represent the flow inside a compressor. Extreme caution should be exercised in the use of these data for the calibration of viscous codes intended for application to compressors. This is because the process of greatest uncertainty, transition, is probably quite different in character for this steady low-turbulence test configuration from that which will be found in the majority of blade rows in a compressor.

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Authors' Closure

The authors would like to thank Professor Cumptsy and Dr. Dong for their comments. In our opinion, these comments are well taken if they prevent even one researcher from believing that matching our data "validates" his code for actual turbomachinery flows. As we tried to make clear in our publications and presentations, we acquired our data for the simplest of flows that exhibit some of the aspects of turbomachinery flow. With this in mind, we would like to see our data used in the same manner that, say, the Stanford Conference boundary layer data would be used by a researcher interested in a turbulent boundary layer with large heat addition—as a step to gain confidence in his code by using it to solve a well-documented and related, but simpler, problem.

The most surprising aspect of our work, considering its relatively simple geometry, was the prevalence and importance of separation "bubbles." Your results then, which are very interesting, are perhaps not as surprising to us as they may be to others. We could not agree with you more that the transition process on turbomachinery blades will be extremely difficult to model. Not only does the periodic unsteadiness in a turbomachine change the character of this transition process, but the three-dimensionality of the flow in a turbomachine also can affect transition. Moreover, it appears likely to us that the current turbulence models, which are after all derived from steady flow experiments, also will prove to be inadequate. Researchers must take great care in moving from the calculation of our simple flow field to the calculation of the flow in actual turbomachines. In spite of this, we hope that our data set will be useful as one step in understanding the physics of and developing models for these complicated flows.

In answer to your question about the accessibility of the results, we are happy to say that the data for all three incidence angles are available in tabulated form in the NASA Contractor Report 184118; see Zierke and Deutsch (1989). Also, COSMIC will soon make a computer tape of the data available.

Additional Reference

Zierke, W. C., and Deutsch, S., 1989, "The Measurement of Boundary Layers on a Compressor Blade in Cascade, Volumes I and II," NASA Contractor Report 184118.