# Overall Aerodynamic Performance of an Annular Flat-Plate Airfoil Cascade

Daniel E. Bergsten,* R. Charles Stauter,* and Sanford Fleeter†
*Purdue University, West Lafayette, Indiana*

## Abstract

THE aerodynamic design of turbomachinery blading is specified by means of design systems wherein the flow is assumed to be two-dimensional with losses determined from empirical correlations. However, with the continuing requirements for improved efficiency and increased thrust-to-weight ratio, it is evident that new analyses that consider the fundamental three-dimensional flow phenomena existing in blade-row flow passages must be developed, verified by concise data, and subsequently implemented in the design process.

Numerical solutions are currently being developed to predict the three-dimensional flow through turbomachine blade rows. To overcome the complexities associated with the flow conditions and the internal geometries, these numerical solutions of necessity involve many computational and physical assumptions.

This paper describes experiments performed in a large-scale, subsonic annular cascade facility specifically designed to provide three-dimensional aerodynamic data suitable for code verification. In particular, to minimize the complexities associated with cascade geometry and complex airfoil profiles, the detailed overall three-dimensional aerodynamic performance of an extensively instrumented flat-plate airfoil cascade has been experimentally determined over a range of incidence angle values. All of the resulting data are analyzed and correlated with appropriate predictions.

## Contents

A flat-plate airfoil cascade was installed in the Purdue Annular Cascade Facility,[1] and the detailed three-dimensional exit region flowfield as well as the hub, mean, and tip airfoil surface chordwise pressure distributions determined at 0, 5, and 10 deg of incidence. The facility, schematically depicted in Fig. 1, is characterized by a tip diameter of 127 cm, a 0.76 hub/tip radius ratio, a nominal axial velocity of 30 m/s, and a 16.1 $m^3/s$ flow rate. The airfoil cascade consists of 36 flat-plate airfoils each with a 15.24 cm span, a unity aspect ratio, and a thickness-to-chord ratio of 3.17%. Thus, both the overall experimental rig and the airfoils are physically large, reflecting one of the primary design considerations. In particular, the flow passages are large, so as to amplify the fundamental flow phenomena as well as preclude the need for extreme miniaturization of instrumentation. In addition, flexibility is provided for optically based advanced instrumentation such as laser Doppler anemometry.

Figure 2 presents the airfoil passage-to-passage circumferential variation of the cascade exit flowfield with incidence angle as parameter at a radial position of $R = 8.3\%$. As expected, for a classical airfoil cascade at 0 deg of incidence, the axial velocity component is symmetric about the airfoil circumferential location. As the incidence angle is increased from 0 deg, the turning of the flow by the airfoil cascade results in the velocity distributions no longer being symmetric about the airfoil circumferential location, with the nonsymmetry increasing with increasing incidence angle value. This nonsymmetry of the airfoil wake region is due to increased boundary-layer development on the suction surfaces of the airfoil, and possible flow separation for the 10 deg incidence angle data.

To demonstrate the three-dimensionality of the cascade exit flowfield, the wake data at four radial locations for each incidence angle were correlated, as per Fig. 3 for the 5 deg incidence angle case. As seen, the local freestream velocity values, $U_{fs}$, become progressively smaller due to the boundary layers on the hub and outer shroud endwalls as the radial positions approach the annulus walls.

The axial velocity component shows interesting radial variations with incidence angle. At 0 deg of incidence, the axial wake profiles are symmetric about the airfoil circumferential location and are essentially identical for all radial positions. At a 5 deg incidence angle value, Fig. 3, the axial wake profiles are nonsymmetric about the airfoil near the hub ($R < 8.3\%$) but symmetric away from the hub region ($R > 8.3\%$). At 10 deg of incidence, the axial component wake profiles are nonsymmetric about the airfoil for all radial locations, with this nonsymmetry amplified in the hub and tip regions. Also, separation may occur in the hub region for the 10 deg incidence angle case, as evidenced by the nonexistence of a local uniform freestream region in the axial component velocity data at $R = 4.2\%$.

Previous investigations have established similarity relationships for mean velocity airfoil wake data. In particular, Lakshminarayana and Davino[2] have presented the coefficients for the Gaussian similarity function for inlet guide vane and stator vane wakes as

$$W/W_{CL} = \exp(-0.693\eta^2)$$

where $W$ = velocity deficit $(U_\eta - U_{fs})$; $W_{CL}$ = airfoil circumferential location velocity deficit; $\eta$ = normalized tangential distance, circumferential spacing/$L_{1/2}$; fs = freestream; $L_{1/2}$ = wake half-width at one-half the depth of $W_{CL}$.

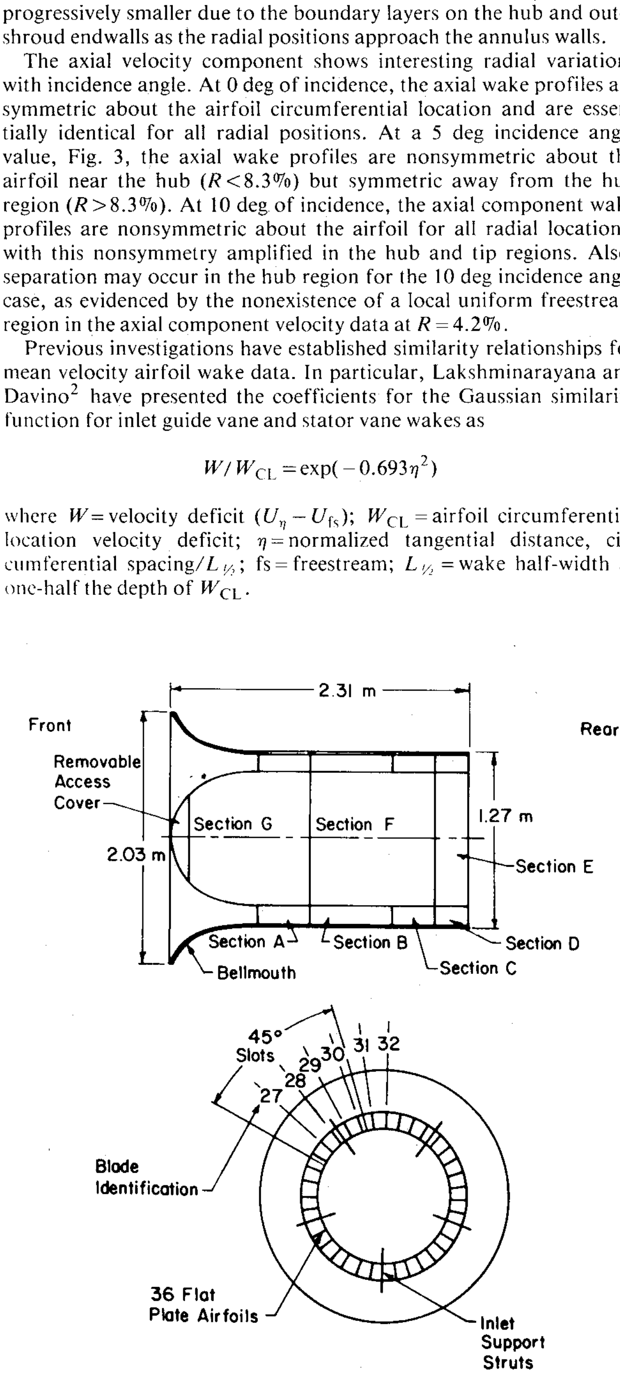


**Fig. 1 Schematic of the annular cascade facility.**

Presented as Paper 83-0179 at the AIAA 21st Aerospace Sciences Meeting, Reno, Nev., Jan. 10-13, 1983; submitted Jan. 14, 1983; synoptic submitted May 11, 1983.  Full paper available from AIAA Library, 555 W. 57th Street, New York, N. Y. 10019. Price: Microfiche, $4.00; hard copy, $8.00. **Remittance must accompany order.**

*Graduate Research Assistant, Thermal Sciences and Propulsion Center, School of Mechanical Engineering.

†Professor, School of Mechanical Engineering and Director, Thermal Sciences and Propulsion Center, School of Mechanical Engineering. Member AIAA.

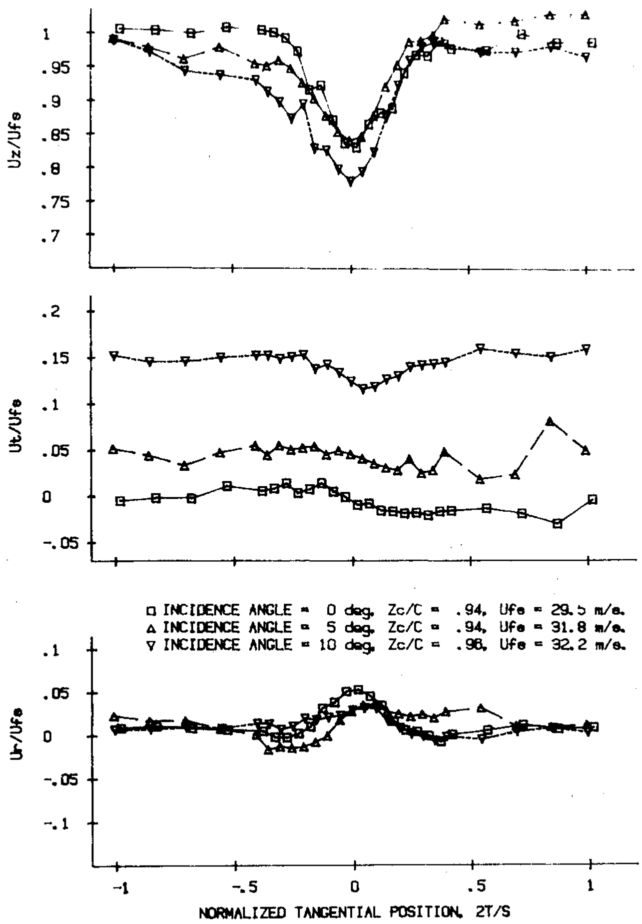


**Fig. 2 Variation of the cascade wake velocity data with incidence angle at $R = 8.3\%$.**

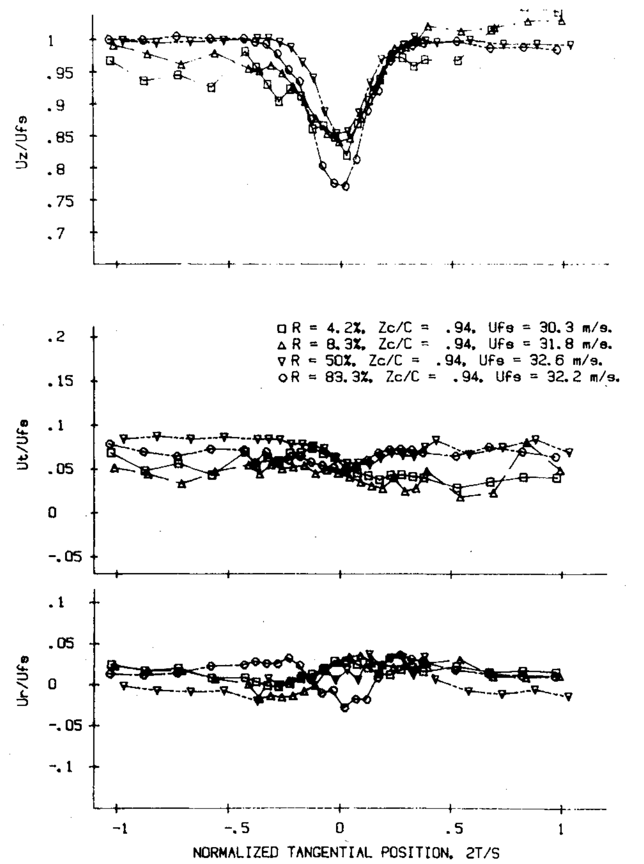


**Fig. 3 Radial variation of the cascade wake velocity data at 5 deg of incidence.**

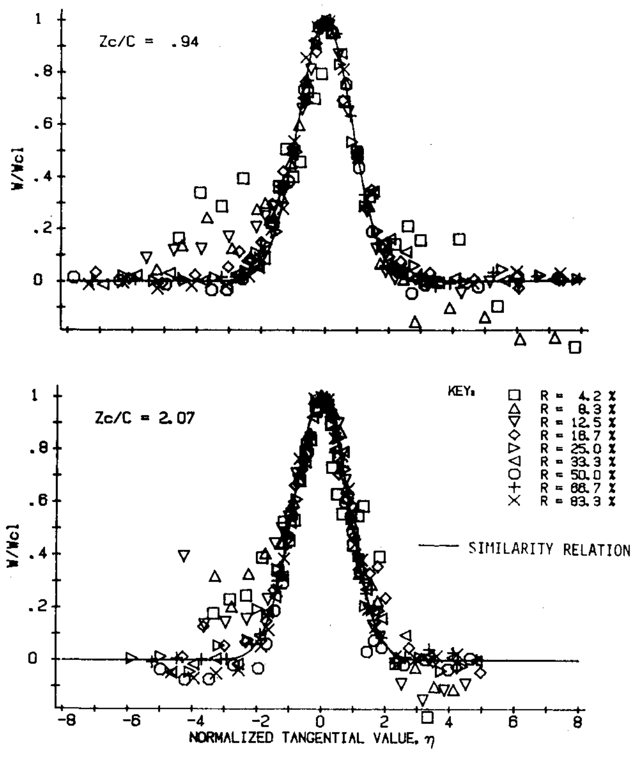


**Fig. 4 Similarity of the 5 deg incidence angle velocity data.**

The classical airfoil cascade wake data away from the endwall regions ($12.5\% < R < 75\%$) exhibit excellent correlation with the Gaussian similarity relations, as seen in Fig. 4 for the 5 deg incidence angle data. The poor correlation between the Gaussian similarity function and the data in the hub and tip regions is due to the three-dimensionality of the flowfield in these regions and the two-dimensionality of the Gaussian similarity function. Furthermore, examination of the definition of $\eta$ shows that as the wake half-width increases, the value of $\eta$ decreases. Hence, an examination of Fig. 4 reveals the increasing of the wake width with downstream distance, evidenced by the narrowing of the Gaussian data distribution with increased downstream distance, $Z_c/C$.

The chordwise distribution of the cascade airfoil surface pressures were measured at the 10, 50, and 90% spanwise locations at each incidence angle value. All of these airfoil surface data have been correlated with mathematical predictions obtained from the NASA numerical programs MERIDL and TSONIC.[3]

Generally good correlation exists between the 0 deg data and the numerical predictions. The data exhibit sharper gradients than the analysis in the leading edge region, and also show a slight increase in value along the chord due to the airfoil surface boundary layer. At 10 deg of incidence, the correlation between the experimental data and the numerical predictions is only fair. The general trends for the pressure and suction surface data show good agreement with the numerical predictions, but the experimental coefficients are consistently higher than the predicted values, particularly on the airfoil suction surface where thick boundary layers exist and leading edge separation may have occurred.

## Acknowledgments

Support of the research reported herein by the NASA Lewis Research Center, with Don Boldman serving as Technical Monitor for the project, is gratefully acknowledged.

## References

[1] Bergsten, D. E., Stauter, R. C., and Fleeter, S., "Aerodynamic Performance of an Annular Classical Airfoil Cascade," AIAA Paper 83-0179, Jan. 1983.

[2] Lakshminarayana, B. and Davino, R., "Mean Velocity and Decay Characteristics of the Guidevane and Stator Blade Wake of an Axial Flow Compressor," ASME Paper. 79-GT-9, 1979.

[3] Katsanis, T. and McNally, W. D., "Revised Fortran Program for Calculating Velocities and Streamlines on the Hub-Shroud Midchannel Stream Surface of an Axial-, Radial-, or Mixed-Flow Turbomachine or Annular Duct," NASA TN D-8430 and TN D-8431, 1977.