direction since the increase occurs mainly in the axial component. This implies that little practical benefit would be derived from the higher blade loading induced by the leakage vortices: There would be a small increase in the torque developed by the rotor but a proportionately larger increase in the axial thrust. The latter effect is clearly connected with the tip leakage losses, representing a form of pressure drag or induced drag. In their compressor cascade, Lakshminarayana and Horlock (1967) observed a rise in the normal force coefficient of similar magnitude to the rise in resultant force coefficient observed here. However, they did not present the components of the force.

Conclusions

The present experiment shows that tip leakage flow is, if anything, even more complex than was already suspected. Furthermore, it is clear that many questions remain to be answered experimentally, such as the influence of the inlet boundary layer thickness, the effect of the blade geometry and loading distribution, and of course the effect of relative motion by the tip wall. Recognizing then that ours is a particular case and that the flow patterns observed may not be universal, the picture which emerged is briefly summarized.

The interaction of the blade and the endwall boundary layer is significantly affected by the presence of the clearance. The classic horseshoe vortex separation was found to be present, in a diminished form, only for the smallest gap and even in this case the pressure-side leg of the vortex was swept over the blade tip to become part of the leakage vortex. The endwall boundary layer fluid which was swept across the passage did roll up to form a passage vortex. This vortex appeared to remain separate from the vortices formed by the tip-leakage flow. Within the tip gap the leakage flow appeared to follow closely the direction of the maximum pressure gradient and the velocity vectors at a given station were roughly coplanar. After emerging from the gap the leakage flow began to roll up into a vortex whose starting point moved rearward with increasing clearance. A new feature noted was that more than one discrete leakage vortex was formed at the larger clearances. The vortices retained their individual identities and resulted in multiple suction peaks on the suction side of the blade. The reduction in pressure induced by the leakage vortices on the suction side was larger than the reduction in pressure occurring simultaneously on the pressure side, with the net result that there was a rise in blade force as the tip was approached. It was found that the rise occurred primarily in the axial component of the force.

It is felt that the present study has given new insights into the nature of the tip leakage flow and its effects on the blade loading. Additional measurements are currently being made to document the gap flow and its subsequent development. When they are completed the experiment should form a suitable and challenging test case for the fully three-dimensional viscous calculation methods which are currently being developed.

Acknowledgments

Financial support for this study provided by the Natural Sciences and Engineering Research Council of Canada under Grant A1671 is gratefully acknowledged. Support for the second author through an NSERC Postgraduate Scholarship is also acknowledged. Numerous useful discussions were held with Dr. S. H. Moustapha of Pratt and Whitney Canada.

References

1 Amrud, K. K., 1985, "Tip Leakage in a Planar Cascade of Turbine Blades," M.Eng. Thesis, Department of Mechanical and Aeronautical Engineering, Carleton University, Ottawa, Canada.

2 Booth, T. C., Dodge, P. R., and Hepworth, H. K., 1982, "Rotor-Tip Leakage: Part 1 – Basic Methodology," ASME Journal of Engineering for Power, Vol. 104, pp. 154-161.

3 Davino, R. M., and Lakshminarayana, B., 1982, "Characteristics of Mean Velocity in the Tip Region of Turbomachinery Rotor Exit," *AIAA Journal*, Vol. 20, No. 4, pp. 528-535.

4 Graham, J. A. H., 1985, "Investigation of a Tip Clearance Cascade in a Water Analogy Rig," ASME Paper No. 85-IGT-65.

5 Hah, C., 1985, "A Numerical Modeling of Endwall and Tip-Clearance Flow of an Isolated Compressor Rotor," ASME Paper No. 85-GT-116.

6 Kacker, S. C., and Okapuu, U., 1982, "A Mean Line Prediction Method for Axial Flow Turbine Efficiency," ASME Journal of Engineering for Power, Vol. 104, No. 1, pp. 111-119.

7 Koch, C. C., and Smith, L. H., Jr., 1976, "Loss Sources and Magnitudes in Axial-Flow Compressors," ASME Journal of Engineering for Power, Vol. 98, No. 3, pp. 411-419.

8 Lakshminarayana, B., 1970, "Methods of Predicting the Tip Clearance Effects in Axial Flow Turbomachinery," ASME *Journal of Basic Engineering*, pp. 467-480.

9 Lakshminarayana, B., and Horlock, J. H., 1963, "Tip-Clearance Flow and Losses for an Isolated Compressor Blade," ARC R&M No. 3316.

10 Lakshminarayana, B., and Horlock, J. H., 1967, "Leakage and Secondary Flows in Compressor Cascades," ARC R&M No. 3483.

11 Moore, J., Moore, J. G., and Timmis, P. H., 1984, "Performance Evaluation of Centrifugal Compressor Impellers Using Three-Dimensional Viscous Flow Calculations," ASME Journal of Engineering for Gas Turbines and Power, Vol. 106, No. 2, pp. 475-481.

12 Pandya, A., and Lakshminarayana, B., 1983, "Investigation of the Tip Clearance Flow Inside and at the Exit of a Compressor Rotor Passage – Part I: Mean Velocity Field," ASME Journal of Engineering for Power, Vol. 105, pp. 1-12.

13 Phillips, W. R. C., and Head, M. R., 1980, "Flow Visualization in the Tip Region of a Rotating Blade Row," *International Journal of the Mechanical Sciences*, Vol. 22, pp. 495-521.

14 Rains, D. A., 1954, "Tip Clearance Flows in Axial Flow Compressors and Pumps," Report No. 5, Hydrodynamics and Mechanical Engineering Laboratories, California Institute of Technology.

15 Sieverding, C. H., 1985, "Recent Progress in the Understanding of Basic Aspects of Secondary Flows in Turbine Blade Passages," ASME Journal of Engineering for Gas Turbines and Power, Vol. 107, No. 2, pp. 248-257.

16 Sjolander, S. A., 1975, "The Endwall Boundary Layer in an Annular Cascade of Turbine Nozzle Guide Vanes," Tech. Report ME/A 75-4, Department of Mechanical and Aeronautical Engineering, Carleton University, Ottawa, Canada.

17 Wadia, A. R., 1985, "Numerical Solution of Two- and Three-Dimensional Rotor Tip Leakage Models," *AIAA Journal*, Vol. 23, No. 7, pp. 1061-1069.

18 Wadia, A. R., and Booth, T. C., 1982, "Rotor-Tip Leakage: Part II – Design Optimization Through Viscous Analysis and Experiment," ASME Journal of Engineering for Power, Vol. 104, pp. 163-169.

DISCUSSION

R. G. Williamson[1]

The paper presents detailed information on tip leakage phenomena in a stationary cascade, and the authors are to be congratulated on their careful approach. With this work as a base, it is natural to ask how the inferred vortex structures would be affected by relative movement between the tip and the casing. Clearly, the interpretation of Fig. 6, with stagnation lines on the casing, could no longer be valid, and the presence of multiple vortices might be questioned.

Some corroborative evidence for multiple tip vortices in a rotating blade environment is afforded by the flow visualization photograph presented as Fig. 14 of [19]. Rotor 51 blading clearly shows two dark streaks near the blade tip. Measurements of these surface markings, and a tentative interpretation of the associated multiple vortex structure, are contained in [20], and reproduced here as Figs. 12 and 13. The diameter of the main vortex structure at the trailing edge was estimated as about 10 mm (0.4 in.), or about eight times the tip gap, which correlates well with the measurements of Sjolander

[1] Division of Mechanical Engineering, National Research Council Canada, Ottawa, Canada K1A OR6.

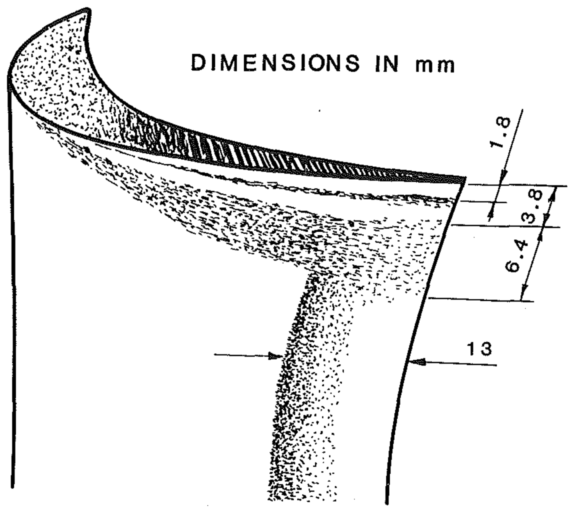

Fig. 12 Flow visualization on rotor blade

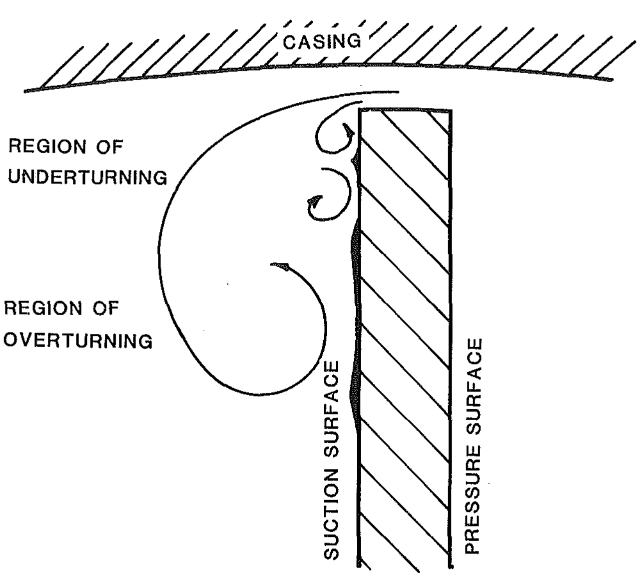

Fig. 13 Possible flow pattern near blade tip

and Amrud. Flow turning of the rotor blade was affected over the outer 20 percent of the span (15 mm or 0.6 in.). It is noted that these data involved a tip clearance of 1.3 mm (0.050 in.), and that the measurements presented in [19] refer to a later build with 1.8 mm (0.070 in.) tip clearance. There is some evidence that the size of the vortex structure increased approximately in proportion to tip clearance. Further work is planned.

References

19 Moustapha, S. H., Okapuu, U., and Williamson, R. G., "Influence of Rotor Blade Aerodynamic Loading on the Performance of a Highly Loaded Turbine Stage," ASME JOURNAL OF TURBOMACHINERY, this issue.

20 Williamson, R. G., "NRC/P&WC Highly Loaded Turbine. Report No. 2: Completion of Performance Mapping—Initial Build," (Company Confidential), NRC LTR-GD-71, June 1982.