DISCUSSION

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Most of the papers on stall have been directed at machines with high hub-tip ratio and it is welcome to see a paper that considers the much more difficult topic of stall for low hub-tip ratio compressors. With a high hub-tip ratio there are many aspects of stalling behavior that are not understood; this is even more true for machines such as those that are the basis of this paper. Soundranayagam and Elder have tried to explain the observed tendency of low hub-tip ratio compressors to stall when conditions at the tip deteriorate. To this end they have used an axisymmetric calculation method to examine the radial redistribution of flow. They conclude that the radial redistribution, referred to here as streamtube contraction, tends to increase the stability of the flow near both the hub and tip. I believe that their conclusions relating to the flow at the hub are entirely wrong and contrary to experimental evidence, while those for the tip are misleading.

When the flow through a rotor is reduced below its design value, a powerful effect is the drop in axial velocity across the rotor root. This may be thought of as a fundamental trend in the way in which rotors respond. It arises from the more rapid increase in work input near the tip than near the hub as the flow rate is reduced, together with the constraints of radial equilibrium, and can be seen using even elementary arguments. Lower axial velocity near the hub than the casing necessarily leads to a radial shift in the streamsurfaces, and to a contraction in the streamsurfaces near the casing. Because of the axial velocity drop between inlet and outlet across the rotor near the hub, a marked rise in flow blockage or even flow separation can occur there. The large amount of blockage associated with any separation will lead to an additional increase in the radial outward shift of the streamsurfaces.

The rotor geometry used by the authors for the meridional calculations in this paper was tested by Smith (1980) in the White Laboratory. (Much of the information in this PhD thesis is given in the more accessible paper by Smith and Cumpsty 1984.) Smith measured a time-mean reversed flow near the hub (an axial velocity moving in the upstream direction) while the rotor was still operating in a stable manner in its unstalled mode. It is not that some relief occurred to make the hub stable, as Soundranayagam and Elder conclude, but that complete flow separation and reversal there do not lead to instability of the entire flow or a transition to rotating stall. The rotor tested by Smith was very definitely one that stalled following flow deterioration at the tip, because casing treatment proved highly effective in extending the operating range.

Some of the confusion is undoubtedly caused by terminology, since the word "stall" has so many uses and meanings. Many blades have some separated flow near the root, particularly at flow rates below the design value; although this is generally undesirable, it is not necessarily serious, and when it occurs it does not seem appropriate to refer to the blade row as stalled. In some cases, such as that described by Smith and Cumpsty, the extent of separation at the root can be substantial, yet the rotor operates on an unstalled characteristic. It seems to be desirable to avoid terms like root stall, since the effect of this is so very different from stall in the sense of the change in operation of the rotor from unstalled flow to fully developed rotating stall. In any event, whenever the word stall is to be used it is essential to make clear what is meant. The word "stable" also needs to be used with caution: It is not legitimate in the present context to talk, for example, about the flow at a blade root being stable. It is the entire flow field that is stable or unstable. The question should rather be whether the flow near the root is such that the entire flow is stable when axisymmetric, or whether the axisymmetric flow is unstable with the root flow in this condition so that flow will alter to an asymmetric one in rotating stall. The flow in the rotor tested by Smith was clearly stable when the flow near the hub was severely separated and the flow did not become unstable until conditions near the tip deteriorated.

The first paragraph of Soundranayagam and Elder's conclusions seems to me to be accurate. The second paragraph, however, seems wrong for the following reasons:

1 There is absolutely no evidence that the rotor root has a tendency "to remain stable." The rotor used by the authors for their calculation showed extensive separation and flow reversal near the hub prior to collapse of the whole flow into rotating stall. It would be more appropriate to say that flow separation in the root does not lead to instability of the entire rotor flow.

2 The rotor root does not behave contrary to expectations based on two-dimensional cascade concepts, although it would be unwise to apply these concepts without recognizing the important three-dimensional effects involved.

3 The tip does not show a larger propensity to stall. What it does show is a controlling influence over the stability of the entire flow. In other words it is with a change in the flow at the tip that the overall flow then exhibits a rapid evolution into what is commonly called rotating stall.

References

Smith, G. D. J., and Cumpsty, N. A., 1984, "Flow Phenomena in Compressor Casing Treatment," ASME *Journal of Engineering for Gas Turbines and Power*, Vol. 106, pp. 532–541.

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The authors rightly point to an effect that should move a root section toward flow separation—the drop in local axial velocity across the blade row. They suggest that the root behaves "contrary to expectations based on two-dimensional blade concepts," possibly due to centrifuging of the boundary layer.

But there is another effect that may invalidate the use of cascade data in the prediction of root performance—the different secondary flow in the two cases. In the cascade test the entry flow is co-lateral and the wall boundary layer is swept into the corner between the wall and the suction surface of the blade, causing a substantial area of separation. In the compressor test the (relative) annulus wall boundary layer is skewed at entry to the rotor root. The streamwise vorticity associated with this entry skew is opposite to that generated in the passage and smaller areas of corner separation may be anticipated (an effect originally observed by Moore and Richardson at M.I.T.). We may however note that if the wall boundary layer grows over an infinitely long rotating hub, then the flow at entry to the rotor root is indeed colateral and the cascade tests will be more representative of compressor performance, as long as the axial velocity ratio is matched.

In the experiments by Wood et al. to which the authors refer, a "rough" rotating stall was observed near the hub of the compressor, but it was on the stator root section. The rotor tip was the first to stall, in a part-span mode.

Authors' Closure

The reduction in axial velocity at the rotor blade root described by Professor Cumpsty is presumably that due to the spanwise rematching of the rotor to satisfy downstream radial equilibrium conditions and he is quite correct in stating that these are independent of viscous effects. The calculations pre-

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