indicates that the unsteady pressure has a stronger influence on the increase in profile loss at higher wake traverse speeds.

## Conclusions

The following conclusions can be drawn based on the simulation study of unsteady cascade flow due to wake/blade interaction.

The combined effects of three different mechanisms are found to be responsible for the generation of unsteady pressure on the blade surface with a wake/blade-row interaction: the wake cutting by the blade leading edge, the change in streamwise velocity near the surface caused by the counterrotating vortices, and the wake velocity defect, the periodic variation of the instantaneous outflow angle induced by the counterrotating vortices.

In the transitional blade boundary layer subjected to wake velocity gust, the onset of transition changes periodically due to temporal variation of local boundary layer momentum thickness. The time-dependent transition caused by the wake velocity defect does not have a significant effect on the global development of the blade boundary layers.

The transition on the blade is strongly influenced by the high turbulence intensity in the wake. Periodic transitional patches are generated by the high turbulence intensity in the passing wakes and transported downstream. The time-dependent transition results in large unsteadiness in the instantaneous local skin friction coefficient and a smoother time-averaged transition curve than the one observed in the steady boundary layer.

Both the wake velocity defect and the wake turbulence are found to have a significant influence on the unsteady blade boundary layers. The wake velocity defect has stronger influence on the magnitude of unsteady momentum thickness, while the wake turbulence is mainly responsible for the large magnitude of unsteady skin friction coefficient in the transition region.

A decrease in axial gap results in an increase in the amplitude of unsteady surface pressure and unsteady momentum thickness. The amplitude of the unsteady skin friction coefficient increases outside the transition region.

At higher reduced frequencies, more lobes appear on the chordwise distribution of unsteady surface pressure. This results in nonmonotonic increase in the chordwise distribution in the amplitude of the unsteady momentum thickness.

An increase in the reduced frequency and the wake inflow angle due to higher wake traverse speed results in a rapid increase in the magnitude of unsteady surface pressure, skin friction coefficient, and the boundary layer momentum thickness.

Unsteady wake/blade interaction has an appreciable influence on the profile loss. The time-averaged profile loss decreases slightly as the axial gap is increased. Increase in the wake/blade count ratio results in significant increase in both the time-averaged profile loss and the frictional drag. Increase in wake traverse speed could result in appreciable increase in the time averaged profile loss.

The results presented in this paper are subject to the performance of the turbulence model, the wake decay model and the simplifications in wake specification procedure (change in rotor blade loading has not been considered, for example). Further improvements in the turbulence model and more accurate wake specification procedure are necessary to improve the accuracy of the numerical procedure.

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## DISCUSSION

### N. A. Cumpsty[1]

These are interesting and useful papers. The ability to predict the behavior of the unsteady flow inside the passages is impressive and I believe it will prove very helpful in calculating the interaction of wakes with blade boundary layers and improving our understanding. My grounds for caution relate to the second paper, which refers specifically to the *physics* of the boundary layer flow. The problem goes beyond what is normally described as turbulence modeling.

Experiments were performed some years ago by Dong (1988) and Li (1990) with traveling wakes disturbing the boundary layers on the surfaces of compressor blades. These measurements demonstrated that the flow physics is not quite how it is assumed in most treatments of the flow, including the present one of Fan and Lakshminarayana. (Some of the results obtained by Dong were reported by Dong and Cumpsty, 1990.) After a turbulent patch or spot passes, there is a period of calmed flow,

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[1] Director, Whittle Laboratory, University of Cambridge, Madingley Rd., Cambridge, CB3 ODY United Kingdom.

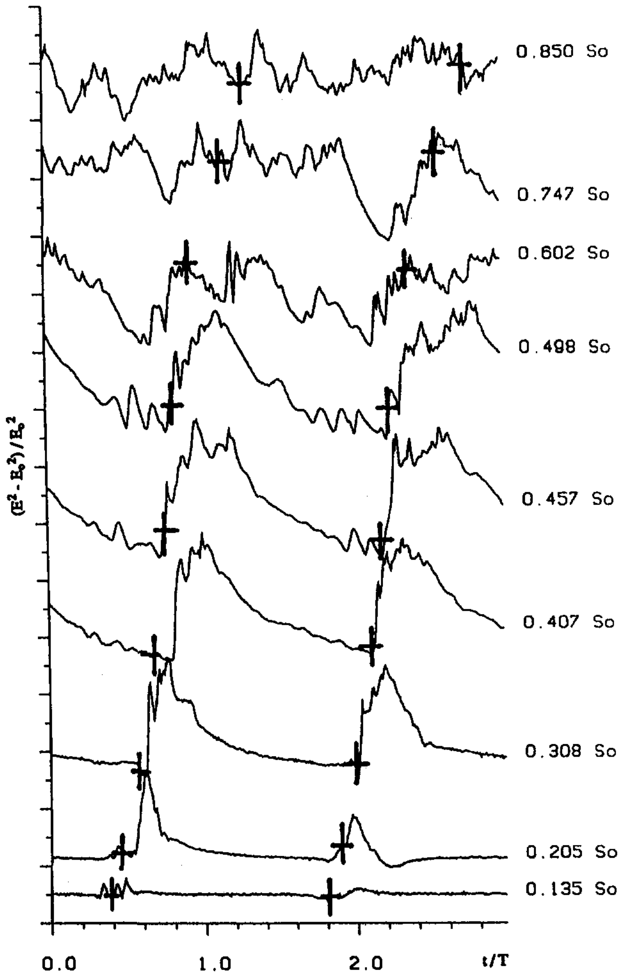

**Fig. 18 Raw traces from a hot-film gage at positions on the suction surface of a rotor blade passing through wakes from upstream**

and for compressor blades this lasts for a time comparable to the time for the free-stream flow to travel the length of the blade passage. Although the flow in the calmed region is laminar, the properties of this calmed region are quite unlike those of a conventional laminar boundary layer. The calmed region was first reported by Schubauer and Klebanoff (1955), but it has received little study of consideration since.

The importance of the calmed region is illustrated in Fig. 18 with results taken from Li (1990). The data are from a hot-film gage attached to the suction surface of a C4 rotor blade at midspan, operating in the presence of wakes created by stationary radial rods upstream. The incidence for this test was 2 deg, close to optimum for the blade. Figure 18 shows raw (i.e., *not* ensemble-averaged) traces from a *single* hot-film gage attached at different chordwise positions on a rotor blade, each position expressed as a fraction of the total suction surface length $s_0$. The ordinate in Fig. 18 is chosen to give an approximate value for the instantaneous skin friction. The abscissa is time, nondimensionalized by the blade passing period. Each of the traces is started at the same time relative to the passing of wakes; the times at which each wake reaches a position are shown by the bold crosses. From a distance back from the leading edge of around $0.205 s_0$ a recognizable turbulent patch is produced (different in each realization in this raw data). What is even more marked is the calm region following each patch of turbulence; there are patches of calm flow right back to $0.850 s_0$. In the calmed flow the skin friction is not small, as it would be in a conventional laminar boundary layer, but at the start of each calmed region it is equal to the skin friction in the preceding turbulent patch. With the passage of time the calm laminar region relaxes back to a conventional laminar boundary layer.

A paper by Cumpsty, Dong, and Li, illustrating the phenomenon of a wake interacting with a blade boundary layer more fully, and attempting to explain some aspects of the flow, has been presented at the ASME International Gas Turbine and Aeroengine Congress and Exposition in Houston (Paper No. 95-GT-443).

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## Authors' Closure

We would like to thank Dr. Cumpsty for his valuable comments. Dr. Cumpsty's discussion points us to the very important issue of modeling the effects of the calmed flow region observed in a transitional boundary layer following the passage of a turbulent spot. The characteristics of the calmed region have been summarized most recently by Halstead et al. (1995). Within the calmed region, the shear stress relaxes from a turbulent to a laminar level. The boundary layer profile in this region is more stable and tends to suppress flow instabilities, both from Tollmien–Schlichting waves and the bypass transition process.

The modeling effort described in the present papers simulates the transitional boundary layer in an ensemble-averaged sense. A description of individual turbulent spot and the calmed region associated with it is beyond the capability of the present approach. It is found that the $k$–$\epsilon$ model does a reasonably good job in simulating the generation and transport of the ensemble-averaged transitional patches. Although no special treatments or assumptions were made for the calmed region, the model does predict a boundary layer recovery region, which bears close resemblance to the experimentally observed calmed region behind an ensemble-averaged transitional patch.

This region can be clearly seen in Fig. 7(*b*) of Part 1. In this figure, the intermittency factor $\gamma$ defined from the shape factor, $(H - H_l)/(H_t - H_l)$, can be used as a measure for the difference in boundary layer profiles between a conventional laminar boundary layer and a turbulent boundary layer, with a zero for a conventional laminar boundary layer and unity for a conventional turbulent boundary layer on a flat plate. In Fig. 7 (*b*), conventional laminar boundary layer regions (say $\gamma < 0.1$) occupy relatively small area close to the leading edge in the space–time contours. No conventional laminar boundary layer exists beyond 36 percent plate length from the leading edge. The (predominantly turbulent) transitional patches, which assume a wedge shape in the space–time contours, start from about 14 percent blade length and extend to the trailing edge. The triangular regions (on the left) bounded by a conventional laminar boundary layer region and two consecutive transitional patches (from top and bottom) closely resemble the experimentally observed calmed region. The boundary layer in these regions is characterized by the recovery from a turbulent boundary layer profile to a conventional laminar boundary layer profile. Upstream of the point $x/L = 0.36$, the boundary layer after the passage of a transitional patch is able to relax to a conventional laminar profile. Downstream of the point $x/L = 0.36$, the next transitional patch catches up and forces it into turbulent before the boundary layer relaxes to a conventional laminar profile. It is interesting to notice that the convecting velocity deduced from the $\gamma = 0.1$ contour is about 0.33 of the free-stream velocity. This is close to the observed trailing edge convecting