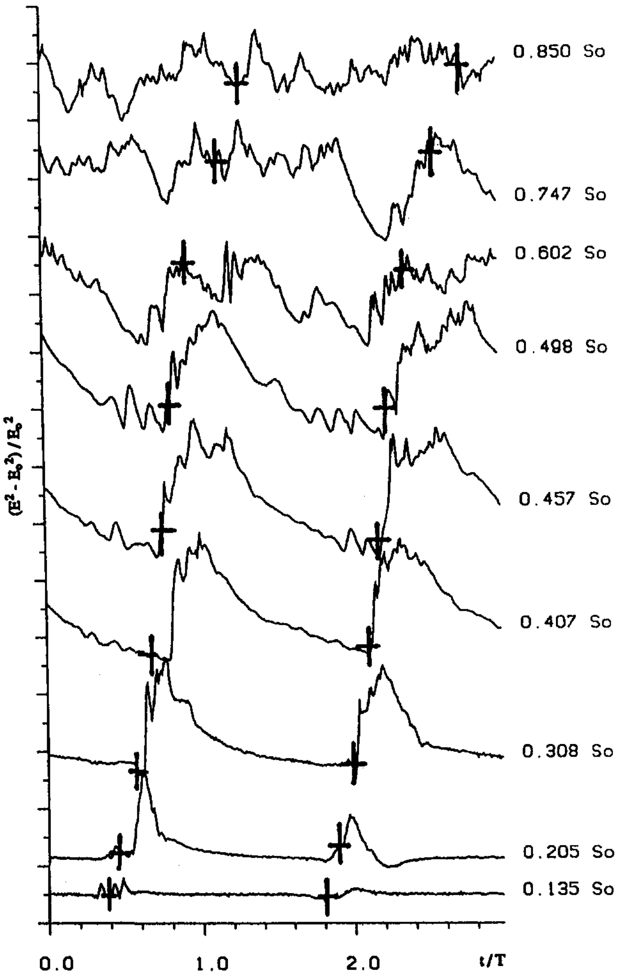

Fig. 18 Raw traces from a hot-film gage at positions on the suction surface of a rotor blade passing through wakes from upstream

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 $0.205s_0$ 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 $0.850s_0$. 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–ϵ 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 γ 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 velocity (0.3 of the free-stream velocity) for a calmed region. The agreement between the trailing edge convecting velocity also indicates the similarity between the predicted recovering region and an experimentally observed calmed region.

The predicted effect of the calmed region or recovering region on bypass transition of the boundary layer between wake-induced transitional patches can be identified from the results shown in Figs. 8(*a*) and 9(*a*) of Part 2. An interesting phenomenon has been observed from the discussion of results shown in Fig. 9(*a*), namely the transition process along the minimum skin friction path is substantially slower than the one for the steady boundary layer. Since the steady boundary layer is subjected to the background free-stream turbulence only, its transitional process is representative of the region between two transitional patches, where the boundary layer is not disturbed by the patches and the calmed regions following them. The fact that there exists a path on the space–time contours (see Fig. 8(*a*)) along which the boundary layer transition is slower than that in the region completely undisturbed by the patches is beyond the conventional explanation. Examination of the space–time contours of skin friction in Fig. 8(*a*) shows that between 14 and 34 percent blade chord, where transition occurs for boundary layer between wake-induced transitional patches, the location of minimum skin friction immediately follows the trailing edge of the wake-induced transitional patches, instead of lying midway between two transitional patches. The location coincides with the recovery region following the transitional patch. The explanation is that the special boundary layer profile in the recovery region tends to suppress turbulence production in the transition region and results in a slower bypass transition than the boundary layer completely unaffected by the transitional patch. The tendency of the predicted recovering region to suppress additional transition further supports its resemblance to the experimentally observed calmed region.

This discussion shows that the present modeling approach did capture some of the ensemble-averaged characteristics of the calmed region. The underlying mechanism in the k–ϵ model that works to mimic this phenomenon is not yet clear, nor is its quantitative capability. Further investigations into these issues are necessary before we can predict this phenomenon with confidence. This is also true for other modeling issues, such as the performance of the model in adverse pressure gradients and control of turbulent production rate to simulate the correct length of transition, etc.

References

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