wake-induced transition on profile loss. When $\hat{f}$ is less than unity, natural transition should occur between wake-passing events. In LP turbines, the values of $\hat{f}$ rarely exceed 0.3. It is for this reason that investigations have revealed the presence of laminar separation bubbles in some LP turbines (Hodson et al., 1994). For the same reason, the work reported by Dong and Cumpsty (1990) on the effect of wakes on compressor blades revealed that separation bubbles exist in compressors. It is rare for the reduced frequencies as defined by Eq. (A) to reach the values used in the present paper. Could the author comment on his use of relatively high reduced frequencies?

References

Dong, Y., and Cumpsty, N. A., 1990, "Compressor Blade Boundary Layers: Part I—Test Facility and Measurements With No Incident Wakes; Part II—Measurements With Incident Wakes," ASME JOURNAL OF TURBOMACHINERY, Vol. 112, pp. 222–240.

Hodson, H. P., 1991, "Aspects of Unsteady Blade-Surface Boundary Layers and Transition in Axial Turbomachines," in: VKI Lecture Series No. 9, *Boundary Layers in Turbomachines,* Von Karman Institute.

Hodson, H. P., Addison, J. S., and Shepherdson, C. A., 1992, "Models for Unsteady Wake-Induced Transition in Axial Turbomachines," *Jnl. de Physique,* Vol. 2, No. 4, Apr., pp. 545–574.

Hodson, H. P., Huntsman, I., and Steele, A. B., 1994, "An Investigation of Boundary Layer Development in a Multistage LP Turbine," ASME JOURNAL OF TURBOMACHINERY, Vol. 116, pp. 375–383.

R. E. Mayle[2] and K. Dullenkopf[3]

We have been unable to explain the discrepancy between your laminar heat transfer data and any laminar boundary layer calculation that accounts for an unheated starting length. The growth of the thermal boundary layer in your experiment does not appear to be correct. Can you explain? This of course would drastically affect the initial portion of the intermittency distribution, which you claim is significantly different than that predicted by the Mayle–Dullenkopf theory. In addition, there are two other points that must be considered in your measurements which you do not address: (1) If wake-induced transition begins before the end of the unheated length, which your results indicate, heat transfer measurements alone are not sufficient to determine the intermittency distribution, and (2) your analysis implies that the increase in heat transfer for a wake-affected laminar flow is the same as that obtained by a turbulent boundary layer flow. The latter point is not true. For further details regarding the effect of turbulent wakes on laminar boundary layers we refer you to the ideas presented by Dullenkopf and Mayle (1992), even though the analysis is for accelerating flows. In conclusion, you are confusing two separate wake effects in your analysis, which have already been addressed. The first, called wake-induced transition, is the effect of periodically passing wakes on boundary layer transition, which has been addressed by Mayle and Dullenkopf (1989, 1991) among others. The second, which might be called turbulent enhancement, is the effect of a periodic increase in the free-stream turbulence on the laminar boundary layer caused by the passing wake (Dullenkopf and Mayle, 1992). These are two distinctly different effects, which should not be lumped into the term "wake-induced transition."

U. Orth[4]

The present paper by K. Funazaki is a welcome and significant contribution toward improvement of our understanding of boundary layer transition induced by turbulent wakes, and presents valuable new measurements. Periodic turbulent wakes can influence boundary layer development due to (1) low-frequency periodic fluctuations of free-stream velocity and pressure gradient, and (2) superimposed high-frequency wake turbulence. The discussion about which of the two is the dominating mechanism of wake-induced transition is an ongoing one. Wake-turbulence-induced transition is often referred to as "direct," whereas transition resulting from periodic unsteadiness of the free stream, and lagging behind the outer wake, is called "indirect." I agree with Funazaki's view that wake turbulence is the main cause of wake-induced transition in his measurements and in those of most other authors.

Concerning Funazaki's reference to measurements of Orth (1993), there are two things I would like to point out:

1 In Fig. 9, Funazaki cites experimental data from Orth (1993) that show that in case of low-intensity wake turbulence ("far wake"), the onset of wake-induced transition occurs noticeably downstream of the point where wake turbulence is ingested into the boundary layer, and that the patch of turbulent fluid within the boundary layer, when it finally does cause transition, has separated from the wake passing over outside the boundary layer. Contrary to Orth's argument, Funazaki assumes that this apparent delay does not actually exist, and that the immediate growth of turbulent patches merely remains undetected due to this taking place nearer to the wall than the measuring plane ($y/d = 0.03$, $y/L = 0.0006$ in Funazaki's notation) in Fig. 9.

I do not agree with this interpretation, and there is further experimental evidence to support the view that the wake did not lead to immediate transition in this case. Orth (1993) took measurements at 18 wall distances down to $y/d = 0.01$ ($y/L = 0.0002$ in Funazaki's notation) and presented them in Figs. 5–8 of his paper. It is observed that the momentary onset of transition actually extends farthest upstream at around $y/d = 0.03$. Orth's Fig. 8 (temporal development of boundary layer momentum thickness and shape parameter) shows conclusively that the onset of transition does indeed occur significantly later in case of a weak disturbance than it does for a strong disturbance. Full details of these measurements were published by Orth (1991).

2 Although Orth's (1993) measurements for the "far wake" case show that turbulent breakdown in the boundary layer lags behind the outer wake, I believe, contrary to Walker (1993), that turbulence, and not periodic fluctuations, was responsible for wake-induced transition. The lag can be explained by the reduced velocity with which the patch of turbulent fluid convects within the boundary layer, as pointed out by N. A. Cumpsty in his discussion of Walker's paper. Wake turbulence is ingested into the laminar boundary layer as it is being formed near the leading edge. However, the thin laminar boundary layer is so stable that turbulent fluid with comparatively low turbulence intensity may convect downstream within it until, with increasing thickness (and Reynolds number), the boundary layer becomes unstable for disturbances of this magnitude, leading to turbulent breakdown.

Since turbulent breakdown in Orth's "far wake" case lags behind the passing wake outside the boundary layer, Walker (1993) characterizes the transition as "indirect," irrespective of which mechanism actually caused it. It may be preferable to avoid the terms "direct" or "indirect" in this context since they can cause confusion, but instead to differentiate between wake-turbulence-induced and periodic-unsteadiness-induced transition.

References

Orth, U., 1991, "Untersuchung des Umschlagvorganges von Platten- und Zylindergrenzschichten bei ungestörter und stationär oder periodisch gestörter Zuströmung," *Doctoral Thesis, TH Darmstadt, Federal Republic of Germany.*

Author's Closure

First, the author appreciates the discussions addressed to the present papers.

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