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?

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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

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Author's Closure

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

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When the author started the study published in this journal, one of the objectives of the study was to construct a simple but reliable tool for predicting wake-affected heat transfer characteristics around HP turbine blades of modern aero-engines. Therefore, the author adopted several parameters used in this paper from the configuration of a typical aero-engine with low bypass ratio. For example, a nozzle-vane-passing frequency to this HP turbine stage is about 13 kHz at climb condition. This high frequency led to the high Strouhal numbers found in this study. As Hodson describes, wake turbulence intensity surely plays an important role in wake-induced boundary layer transition process. Through the present study, the author believes, the author has succeeded to a great extent in revealing how wake turbulence intensity affects the boundary layer transition. However, many factors, including wake turbulence itself, still remain less investigated up to this moment. Thus, the author has been continuing his study, especially focusing on the low-Reynolds-number case containing the appearance of separation or pressure gradient effects.

Mayle and Dullenkopf claim that the author mixed up the two distinct wake effects into one phenomenon termed ''wake-induced transition.'' The answer is negative. As shown in Fig. 14 of Part I, the author clearly distinguished so-called wake-induced transition from the periodic turbulence enhancement. When information of a wake-affected boundary layer is obtained only from the test surface via heat transfer or shear stress, however, it is actually difficult to draw a distinction between these two effects, especially when a time-averaging or phase-lock-averaging technique is applied to the experimental data. Despite some discrepancy appearing in heat transfer measurement, Figs. 11 and 13 in Part I meaningfully exhibit the differences in heat transfer caused by the differences in wake characteristics, which cannot be attributed only to an upward shift of the transition onset. Hot-wire probe measurements in the study of Part II also support this observation. A similar event must be happening in actual cases and this should be incorporated into the model in a rational manner in order to make a more reasonable estimation of wake-affected heat transfer around turbine blades. One might say the present model heavily simplifies the interaction between periodic wakes and a laminar boundary layer. According to the work by Dullenkopf and Mayle (1992), periodic wake turbulence significantly enhances heat transfer of a laminar boundary layer, which depends almost on wake turbulence intensity. This is one of the reasons why the author introduced the value of 4 percent as the threshold of the wake turbulence, although this value is a somewhat empirical one and should be checked with other experiments.

The author understands that Mayle and Dullenkopf pioneered a wake-induced transition model through their excellent works. The author is also aware that several researchers utilized the Mayle and Dullenkopf model and succeeded in predicting characteristics of wake-affected boundary layers to some extent. However, their studies did not tell much about the transition onset caused by the wake passage, which was also his great concern in this study. The author does not feel that it has been fully determined through the present study though.

As for the propagation speeds of the leading edge and trailing edge of the turbulence region, the author adopts $\beta_F = 1.0$ and $\beta_E = 0.55$, respectively. As mentioned in the paper, heat transfer as well as hot-wire probe measurements revealed the validity of the usage of these values in the intermittency model. The author agrees with Hodson's comment that the value $\beta_F = 1.0$ is open to question. After the studies of this paper the author conducted several experiments and has come to an understanding that one can use $\beta_F = 1.0$ as the propagation speed ratio of the leading edge of a wake-induced turbulent region when the suction surface of a turbine blade is of concern. However, in the case of the suction surface of a compressor blade, which seemingly corresponds to the case of ''far wake'' in Orth's study, this is not always the case. Recent investigation done by Funazaki and Kitazawa (1995) has discovered that the direction of the wake-generating bars relative to the test surface affects the wake-induced boundary layer transition. They found that $\beta_F \cong 0.9$ should be used instead when the boundary layer is influenced by wakes from the bars moving away from the test surface. The present author is aware of some papers that are negative to this finding (Mayle, 1991); however, the author believes it is worthwhile continuing his efforts to examine the effect of the direction of wake-generating bar in more detail.

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