1 Wake passing directly induces turbulent patches beneath the wake, but their onset locations and evolving behavior depend heavily on the incident wake turbulence intensity.

2 Measured states of wake-affected boundary layer in the distance–time diagrams are quite similar to the presumed ones in the transition model proposed in Part I, except for the wake-induced transition points, which was previously assumed to be independent of the wake properties.

3 A threshold for defining turbulent region is proposed for convenience in terms of the turbulence intensity, which yields somewhat plausible results when compared to the data in the heat transfer experiments.

4 Based on the observations in this study, a slight modification to the transition model is made with respect to the transition onset. A quasi-steady approach using the criterion of Abu-Ghannam and Shaw is adopted with great success predicting the onset location of the wake-induced turbulent patch.

Acknowledgments

This study is financially supported by IHI, Ishikawajima-Harima Heavy Industries, monitored by S. Yamawaki and R. Henk. Contributions from T. Meguro as well as Y. Yamashita are to be acknowledged.

References

Abu-Ghannam, B. J., and Shaw, R., 1980, "Natural Transition of Boundary Layers—The Effects of Turbulence, Pressure Gradients, and Flow History," *Journal of Mechanical Engineering Science,* Vol. 22, pp. 231–228.

Addison, J. S., and Hodson, H. P., 1990a, "Unsteady Transition in an Axial-Flow Turbine: Part I—Measurements on the Turbine Rotor," ASME JOURNAL OF TURBOMACHINERY, Vol. 112, pp. 206–214.

Addison, J. S., and Hodson, H. P., 1990b, "Unsteady Transition in an Axial-Flow Turbine: Part II—Cascade Measurements and Modeling," ASME JOURNAL OF TURBOMACHINERY, Vol. 112, pp. 215–222.

Addison, J. S., and Hodson, H. P., 1992, "Modeling of Unsteady Transition Boundary Layers," ASME JOURNAL OF TURBOMACHINERY, Vol. 114, pp. 580–589.

Dong, Y., and Cumpsty, N. A., 1990, "Compressor Blade Boundary Layers: Part 2—Measurements With Incident Wakes," ASME JOURNAL OF TURBOMACHINERY, Vol. 112, pp. 231–240.

Gostelow, J. P., Hong, G., Melwani, N., and Walker, G. J., 1993, "Turbulent Spot Development Under a Moderate Adverse Pressure Gradient," ASME 93-GT-377.

Kline, S. J., and McClintock, F. A., 1953, "Describing Uncertainties in Single Sample Experiments," *Mechanical Engineering,* Jan., pp. 3–8.

Mayle, R. E., and Dullenkopf, K., 1990, "A Theory for Wake-Induced Transition," ASME JOURNAL OF TURBOMACHINERY, Vol. 112, pp. 188–195.

Mayle, R. E., 1991, "The Role of Laminar–Turbulent Transition in Gas Turbine Engines," ASME JOURNAL OF TURBOMACHINERY, Vol. 113, pp. 509–537.

Meyer, R. X., 1957, "The Effect of Wakes on the Transient Pressure and Velocity Distributions in Turbomachines," ASME *Journal of Basic Engineering,* Vol. 80, pp. 1544–1552.

O'Brien, J. E., and Capp, S. P., 1989, "Two-Dimensional Phase-Averaged Turbulence Statistics Downstream of a Rotating Spoked-Wheel Wake Generator," ASME JOURNAL OF TURBOMACHINERY, Vol. 111, pp. 475–482.

Obremski, H. J., and Fejer, A. A., 1964, "Transition in Oscillating Boundary Layer Flows," *Journal of Fluid Mechanics,* Vol. 18, pp. 438–448.

Orth, U., 1993, "Unsteady Boundary-Layer Transition in Flow Periodically Disturbed by Wakes," ASME JOURNAL OF TURBOMACHINERY, Vol. 115, pp. 707–713.

Schlichting, H., 1979, *Boundary-Layer Theory,* McGraw-Hill, New York.

Walker, G. J., 1993, "The Role of Laminar–Turbulent Transition in Gas Turbine Engines: A Discussion," ASME JOURNAL OF TURBOMACHINERY, Vol. 115, pp. 207–217.

DISCUSSION

H. P. Hodson[1]

The author has produced an interesting series of experimental results and observations based on the use of simple models of wake-induced transition. I have had an interest in the impact of wake-induced transition on profile loss and proposed (Hodson, 1991) the first model used by the author in Part I to describe wake-induced transition. This model was applied to test cases with realistic pressure distributions operating with relatively strong incoming wakes using a more general form of Eq. (2) of the present paper (see Hodson et al., 1992, and Eq. (A) below). The model gave satisfactory predictions of loss. It is encouraging that the present author observes similar agreement in the case of heat transfer on a zero-pressure gradient flat plate.

All the simple models incorporate the assumption that wake-induced transition takes place via the formation of a turbulent zone, uniform in the spanwise direction, that grows in streamwise extent as it moves downstream. Many classical boundary layer transition studies lead us to expect that individual turbulent spots should form under the influence of incoming wakes. Following the work of Addison and Hodson, Hodson (1991) and Hodson et al. (1992) examined extensions of these simple models to include the unsteady production of turbulent spots in a similar manner to that outlined in Fig. 10 of Part II. These extensions revealed that in the case of very intense wakes, such as those investigated by Pfeil and his co-workers, by Orth, and by the present author, the rate of turbulent spot formation is such that the boundary layer under the wake very rapidly becomes fully turbulent. This explains the success of these simple models. Hodson et al. also examined cases in turbines and compressors where the wake intensity around the start of transition was much less than that investigated by the present author. Consequently, the rate of spot formation was much lower, and this is believed to explain why individual turbulent events (spots) can be observed some distance downstream of the origin of wake-induced transition, particularly in low Reynolds number experiments.

The studies of Hodson (1990, 1991) and Hodson et al. (1992) examined test cases where Re_θ at the start of wake-induced transition seemed to range from 93 to 153. In the present papers, a model is proposed (see Fig. 14 in Part I and Fig. 10 in Part II) whereby a turbulent strip forms underneath the wake at the leading edge. The present data and published correlations do not support the validity of this aspect of the model. Indeed, the hot-wire data presented in Part II show that the turbulent intensities within the boundary layer near the leading edge do not exceed 5 percent. Could the author provide additional data to support the adoption of his model?

Could the author comment on the values he has used for the factors β_E and β_F? Following an examination of the then available data, I chose to set the factors equivalent to β_E and β_F in Eq. (2) equal to 0.5 and 1.0, respectively (Hodson, 1990). The factor $\beta_E = 0.5$ was chosen because it means that the rear of the wake-affected zone propagates at a speed equal to that of most turbulent spots. The factor $\beta_F = 1.0$ was used since it equals the speed of propagation of the wake and was thought to represent the speed of the front of the wake-induced disturbance. This value in particular is open to question. Orth, for example, quotes a value of $\beta_F = 0.88$. Traditional values for speeds of propagation of the leading and trailing edges of turbulent spots are $\beta_F = 0.88$ and $\beta_E = 0.5$, respectively. In practice, the factors β_F and β_E only appear in that part of Eq. (2) which is enclosed by parentheses, and the value of this part of the equation directly affects the intermittency. My own values for β_F and β_E, those of the present author, and those for a typical turbulent spot produce values of 1.0, 0.82, and 0.86, respectively, for that part of Eq. (2) which is enclosed by parentheses.

Notwithstanding these reservations, simple models may still be used to assess the probable significance of wake-induced transition. If natural transition or separation occurs at a distance x_{ln} from the leading edge, while wake-induced transition occurs at x_{tw}, then the maximum value of the time-mean intermittency that can be reached prior to the start of natural transition or separation is given by the value of the reduced frequency parameter f, i.e.,

$$\bar{f} = \bar{\gamma}(x_{\mathrm{ln}}) = \frac{1}{T}\int_{x_{tw}}^{X_{\mathrm{ln}}} \left[\frac{1}{\beta_E} - \frac{1}{\beta_F}\right] \frac{dx}{U} = \frac{1}{T}\,\frac{x_{\mathrm{ln}} - x_{tw}}{U} \quad \text{(A)}$$

Hodson (1990) used the parameter $\hat{f}$ to correlate the effects of

---

[1] Whittle Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 ODY United Kingdom; Mem. ASME.

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.

---

[2] Professor Emeritus of Mechanical Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180.

[3] Dr.-Ingenieur, Institut für Thermische Strömungs Maschinen, Universität Karlsruhe, 76128 Karlsruhe, Federal Republic of Germany.

[4] MAN Gutehoffnungshütte AG, Bahnhofstr. 66, 46145 Oberhausen, Federal Republic of Germany.