Unsteady Boundary Layers on a Flat Plate Disturbed by Periodic Wakes: Part II—Measurements of Unsteady Boundary Layers and Discussion

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As the second part of the study, detailed hot-wire anemometry measurements of wake-affected boundary layers on the flat plate are made. These measurements are organized in order, first, to check the standpoint of the modeling of the wake-induced transition proposed in Part I, and second, to observe wake–boundary layer interaction in detail from a viewpoint of direct and indirect effect of the wake passage upon turbulent spot generation within the boundary layer, as described by Walker (1993). The validity of the presumed state of the wake-affected boundary layer in the distance–time domain, which constitutes the basis of the transition model, is confirmed to great extent. However, it is also found that the criterion for the onset of the wake-induced transition adopted in Part I should be reconsidered. Some successful attempts are therefore made to specify the transition onset.

Introduction

In Part I, wake-affected heat transfer distributions on the test plate subjected to periodic wakes were measured, and on the basis of those data, a new wake-induced transition model in terms of an intermittency factor was proposed. Although this transition model, which takes the effect of wake duration into account, has successfully reproduced the experimental data, further investigation is necessary because that model employs several assumptions about the wake-induced transition point and wake duration. In addition, as pointed out in Part I, some argument is necessary about direct and indirect effects of the wake-passing upon the boundary layer transition, which was mentioned by Orth (1992) and by Walker (1993). For the purpose of examining these issues, it is useful to conduct detailed boundary layer measurement by use of hot-wire anemometry techniques.

In this study, a large number of experimental data about the instantaneous velocity are obtained, which are then processed to obtain ensemble-averaged velocity and turbulence intensity. Attention is focused on the wake-induced transition onset as well as on the growth pattern of the induced turbulent spots or turbulent patch along the flow direction. These observations are compared with the transition model proposed in Part I and with the heat transfer data. A somewhat unique approach is used to determine a threshold of turbulence intensity that defines the extent of the turbulent region of the boundary layer in the distance–time domain.

The present study shows that the transition model works fairly well, but it also reveals a necessity to modify the criterion for the transition onset. Taking into account quasi-steadiness of wake turbulence diffusing into the boundary layer, the transition model is corrected by the well-known correlation for natural transition by Abu-Ghannam and Shaw (1980). With this modification, the model describes the experimental findings, especially the upward movement of the transition onset by the intense wake, quite well.

Experimental Investigation

Test Apparatus and Measuring System. The experimental setup in the present study is schematically shown in Fig. 1, which is quite similar to that of Part I. An I-type hot-wire probe is used for the measurement of wake-affected boundary layers on the flat plate. The number of measuring points amounts to 220: 10 points in the normal direction from $y/L = 0.2 \times 10^{-3}$ to $y/L = 4.8 \times 10^{-3}$ at each of 22 streamwise locations from $x/L = 0.0$ to $x/L = 0.6$. A computer-controlled traverse unit positions the probe along the y coordinate. The measurement origin ($y = 0.0$) is determined with great care at every streamwise location because of slight waviness in the surface of the test plate. The instantaneous velocity data obtained are ensemble-averaged (or phase-locked-averaged) and processed as before (see Eqs. (3)–(5) in Part I), which yields time-resolved velocity as well as turbulence intensity within the boundary layer.

Test Conditions. Throughout this experiment, the inlet flow velocity U_∞ is fixed at 30 m/s and the Reynolds number based on the plate length is then 2×10^6. All flow conditions adopted here are listed in Table 1, where the Strouhal number is defined as

$$S = \frac{fL}{U_\infty}, \quad f = \frac{nn_c}{60}. \tag{1}$$

Note that due to a mechanical restriction of the traverse unit, measurements of the boundary layers over $x/L = 0.0$ to 0.15 are not conducted for the case of $l_D/L = 0.12$.

Uncertainty Analysis. Uncertainty of the measured velocity data is estimated by the method of Kline and McClintock (1953), and it is about ±6 percent.

Results

Measurements of Boundary Layers Near the Leading Edge (x/L = 0.0–0.15). Figure 2 shows the contours of

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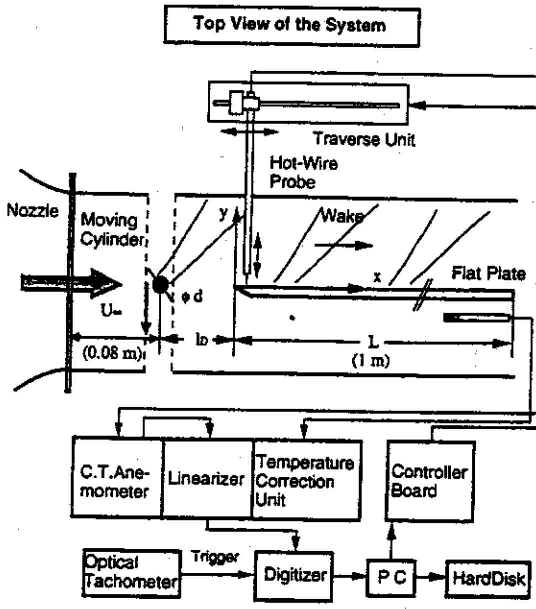

Fig. 1 Schematic layout of the test apparatus and the measurement system

Table 1 Test conditions

No.	n [rpm]	n_c	S	l_D/L
1	1500	3	2.5	0.12
2	1260	3	2.1	0.12
3	1020	3	1.7	0.12
4	900	3	1.5	0.12
5	1020	3	1.7	0.24
6	1020	3	1.7	0.48

phase-locked-averaged turbulence intensity within the $x-y$ plane at several instants during one wake-passing period for the test case of No. 5, where d = 2 mm and l_D/L = 0.24. In this figure solid lines marked with $\langle \delta_{95} \rangle$ indicate the contours of 95 percent free-stream velocity, from which one may spot incident wakes from the cylinders as well as a boundary layer on the test plate. Note that the scales for the x coordinate and the y coordinate are different. At the instant of t/T = 0.45, a wake with more than 4 percent turbulence intensity reaches the leading edge of the plate. As the wake is convected downstream, its turbulence intensity gradually decreases. At t/T = 0.50, a small region with 4 percent turbulence intensity marked with S as well as with slight shade appears at the foot of the wake. After that, the small region moves downstream about at a half speed of the free-stream so that it tends to retard behind the wake; at the same time it keeps growing until it penetrates the free stream at t/T = 0.60. This sequence means that the highly turbulent region is a wake-induced turbulent patch, i.e., a group of turbulent spots induced by a direct interaction between the wake and the boundary layer. It is revealing to recast the above data into distance–time diagrams for turbulence intensity on the horizontal plane closest to the wall ($y/L = 0.2 \times 10^{-3}$) as shown in Fig. 3. This figure clearly shows the appearance and the growth of the turbulent patch. From this diagram, it is quite natural to think that the turbulent patch is caused by the wake passage. The occurrence of a turbulent patch around at x/L = 0.03 can be seen during t/T = 0.45 to 0.50. Being convected downstream, such a turbulence patch gradually extends in length. This is because a downstream edge of the turbulent patch or the patch leading edge moves almost with the wake, while the trailing edge moves slower than the wake. As will be detailed later, the moving speeds of the leading and trailing edges are derived from these diagrams and are respectively found to be about 100 and 54 percent of the free-stream velocity. These values agree with the heat transfer measurements in Part I. As the distance from the surface increases, the effect of the turbulent patch tends to disappear as only a region of high turbulence intensity associated with the wake can be recognized.

Figure 4 shows contours of the phase-locked-averaged turbulence intensity in the case of No. 6, where the unsteady condition is the same with the case of No. 5 except that the distance between the wake generator and the flat plate is enlarged (l_D/L = 0.48). Although the instant when the wake reaches the plate leading edge is different from the previous cases of Figs. 2 and 3 due to the extra distance, relative wake positions in Fig. 4 are almost the same as those of the corresponding diagrams in Fig. 2. Compared to the previous cases, wake turbulence in Fig. 4 decays slightly. Under such circumstances, it takes longer for a 4 percent turbulence intensity region to appear inside the boundary layer after the wake arrives at the leading edge. Moreover, the growth rate of the induced turbulent patch in this decayed wake case is smaller than that of the previous wake case shown in Fig. 2.

At first glance, such a phenomenon seemed to be explained by the difference in diffusive time scale of the turbulent kinetic energy between the two wake cases as pointed out by Addison and Hodson (1990a, b). They have shown that the time needed for the turbulent kinetic energy of wake to diffuse into a boundary layer is in inverse proportion to the corresponding eddy viscosity inside the wake. In the case of a two-dimensional

Nomenclature

C = characteristic length
C_d = drag coefficient
d = diameter of cylinder
f = wake passing frequency
k = reduced frequency
L = length of the flat plate = 1 m
l_D = distance between the wake-generating cylinder and the leading edge of the flat plate
n = revolution number
n_c = number of cylinders
Re = Reynolds number = $U_\infty L/\nu$
Re_x = Reynolds number based on the length measured from the leading edge of the plate
Re_θ = momentum thickness Reynolds number
S = Strouhal number
S_w = wake passing Strouhal number = $L/(U_\infty T)$
T = wake passing period
t = time
Tu = ensemble-averaged turbulence intensity
U_∞ = free-stream velocity
x_S = turbulent spot initiation point
x_{tw} = start point of wake-induced transition
β_E, β_F = trailing edge and leading edge propagation velocity ratios of turbulent spot to the free-stream velocity
$\gamma_w(x)$ = local intermittency factor of wake-affected boundary layer
ν, ν_t = kinematic viscosity, eddy viscosity
τ_w = wake duration
ω = angular frequency

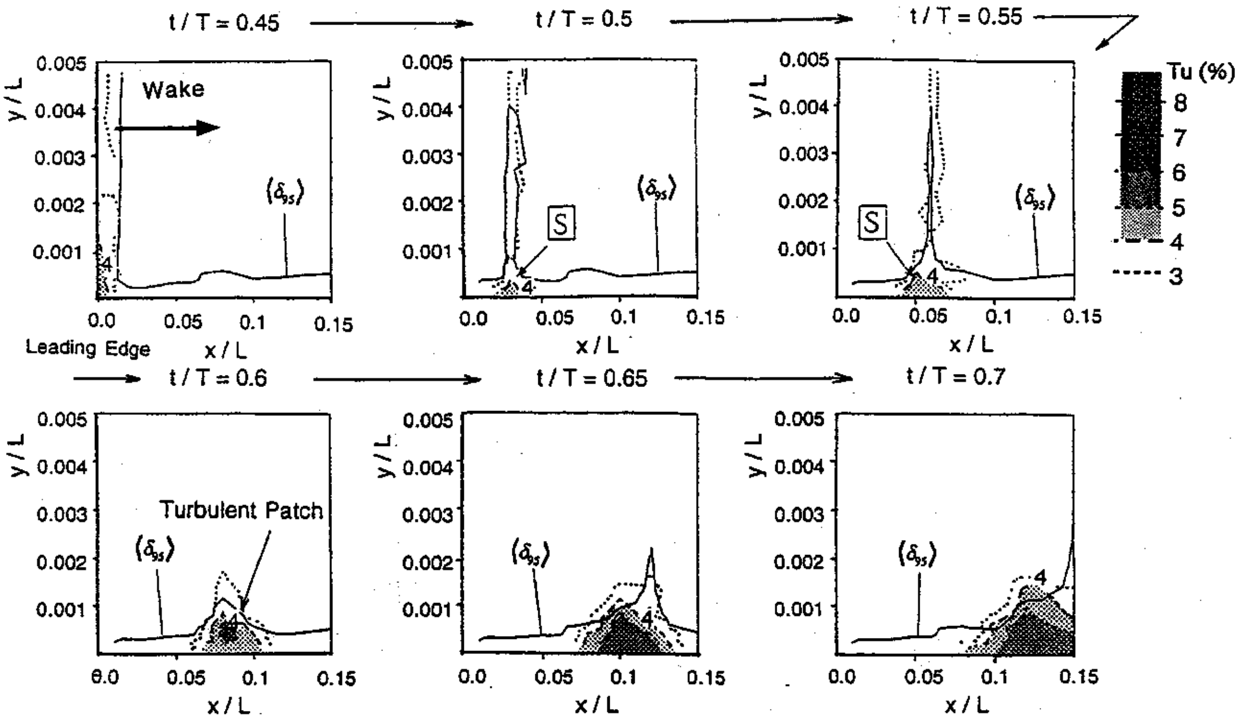

Fig. 2 Phase-locked-averaged contours of turbulence intensity within the x–y plane for several instants during one wake-passing period (Case 5 in Table 1 and d = 2 mm)

wake from a circular cylinder, its eddy viscosity ν_t is given by Schlichting (1979):

$$\nu_t \sim C_D U d, \tag{2}$$

which means that the enlarged distance between the plate and the cylinder has little effect on the diffusive time scale. Accordingly, the difference in growth rate of turbulent patch can be attributed to the difference in magnitude of the wake turbulence intensity. It is again clear that the wake passage surely causes a turbulent patch inside the boundary layer in a direct manner even in this weak wake case.

Figure 5 shows a distance–time diagram of turbulence intensity obtained for case 5, which has same test condition as Fig. 3, except that the cylinder diameter d = 5 mm. It is difficult to identify the appearance of any wake-induced turbulent patches from this figure because of the wider and more intense wake,

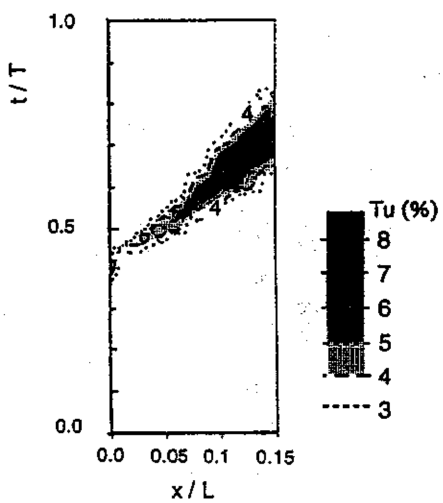

Fig. 3 Phase-locked-averaged contours of turbulence intensity measured at $y/L = 0.2 \times 10^{-3}$ (Case 5, d = 2 mm)

in contrast with the case 11, where a turbulent patch appeared at the foot of the wake center. Since the turbulent patches move downstream more slowly than the wake, they finally come out of the wake as seen around t/T = 0.65 through t/T = 0.70. It is also clear from the diagram that the highly turbulent state lasts for about one tenth of the wake passing period over the surface to $x/L \cong 0.04$, from which the duration of the turbulent state starts to expand.

Measurements of Boundary Layers Near the End of the Wake-Induced Transition. Figure 6 is a sample diagram that illustrates movements of the wake-induced turbulent regions over the region from x/L = 0.30 to x/L = 0.60 for case 3. It is attached with the reproduction of Fig. 3 for better understanding of the entire evolution process of the turbulent patch. This figure shows that the turbulent patches appearing in a periodic manner continue to grow from their initiation until the end of the transition process. In this case another highly turbulent region appears around x/L = 0.5 before the two consecutive turbulent regions merge, which could be attributed to the effect of steady flow transition phenomena. As the Strouhal number increases, it is found that the merger points for S = 2.1 (case 2) and S = 2.5 (case 1) are located around at x/L = 0.55 and x/L = 0.45, respectively. Therefore, such a turbulent region tends to disappear due to the earlier merger of those wake-induced turbulent regions. This matches the observation in Figs. 19 and 20 of Part I.

Comparisons Between the Experimental Data and the Model

In this section, the present experimental data are examined from the viewpoint of the wake-induced transition model proposed in Part I.

One might recall that the transition model is developed on a basis of the presumed state of the wake-affected boundary layer in a distance–time diagram as shown in Fig. 14 of Part I. This presumption can be checked by comparing that figure with the contours of the turbulence intensity measured at $y/L = 0.2 \times$

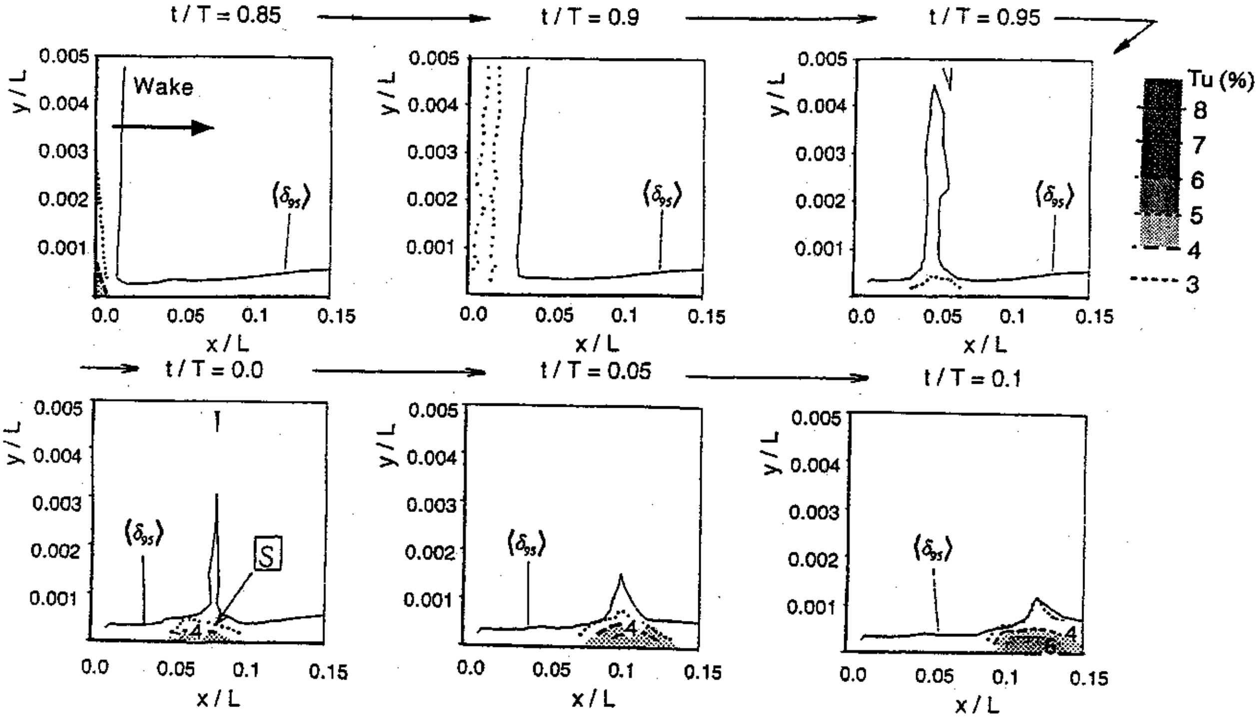

Fig. 4 Phase-locked-averaged contours of turbulence intensity for several instants during one wake-passing period (Case 6, *d* = 2 mm)

10^{-3} in Fig. 6. From such a comparison, it is seen that the measured growing patterns of turbulent regions are similar to the presumed one, supporting the standpoint upon which the proposed transition model is based. But quantitative evaluations are also necessary in order to check the validity of the values employed in the transition model, namely wake duration τ_w and a turbulence propagation velocity ratio β_E. In addition, the criterion for determining wake-induced transition point (Eq. (14) in Part I) should be checked. For that purpose, the experimental data obtained for all flow conditions of Table 1 with various configurations of the test section are compared with an idealized state of the wake-affected boundary layer as in Fig. 7 (note that Fig. 7 is actually a rough sketch of Fig. 6). In executing this task, however, one will be soon aware of the necessity to make a clear definition of the extent of the wake-induced turbulent region like the shaded region in Fig. 7. Hence we begin the following examination with a discussion of this problem.

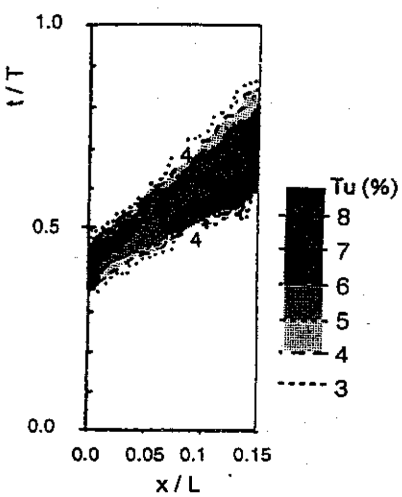

Fig. 5 Phase-locked-averaged contours of turbulence intensity (Case 5, *d* = 5 mm), with the same flow condition as Fig. 3 except for the cylinder diameter

Definition of Turbulent Region and Wake Duration. So far, there have been few arguments about a definition of the turbulent region in wake-induced transition problems. It seems difficult to give any rigorous definition for the turbulent region; hence a somewhat practical approach is employed in this study, that is, the present contours of the turbulence intensity are compared with the results of the heat transfer measurement of Part I in order to find out what level of the turbulence intensity gives almost the same result with the heat transfer measurement at the end of the wake-induced transition. From Fig. 17 in Part I, for example, the transition completes around at Re = 1.0×10^6, which corresponds to $x/L = 0.50$. Comparing this result with the corresponding turbulence contours shown in Fig. 8, it is seen that regions with more than 4 percent turbulence intensity exhibit almost the similar results to the heat transfer data because they merge around $x/L = 0.50$. After several inspections, we have confirmed that using 4 percent turbulence intensity as the threshold of the wake-induced turbulent region yields reasonable agreement with the heat transfer data.

Applying this definition to the turbulent region in Fig. 6 for example, we have tried to determine the extent of the turbulent region. Slopes of the edges of the turbulent region in the distance–time domain are then calculated for each of the test conditions with a curve-fitting technique, giving the edge-propagation velocities shown in Fig. 7. These results are listed in Table 2 in terms of the ratio of the trailing edge velocity to a freestream velocity, β_E, where the ratio for the leading edge, β_F, was almost unity in all cases. Although small scattering appears in the data, its average becomes $\beta_E \cong 0.54$, which is very close to the presumed value ($\beta_E = 0.55$) in the transition model. This also gives somewhat favorable evidence for using the 4 percent intensity as the threshold for the turbulent region. Apart from this finding, Gostelow et al. (1993) have recently used 4 percent disturbance level as an indicator of turbulent spot edges. Despite different experimental situations in both studies, this supports our present approach.

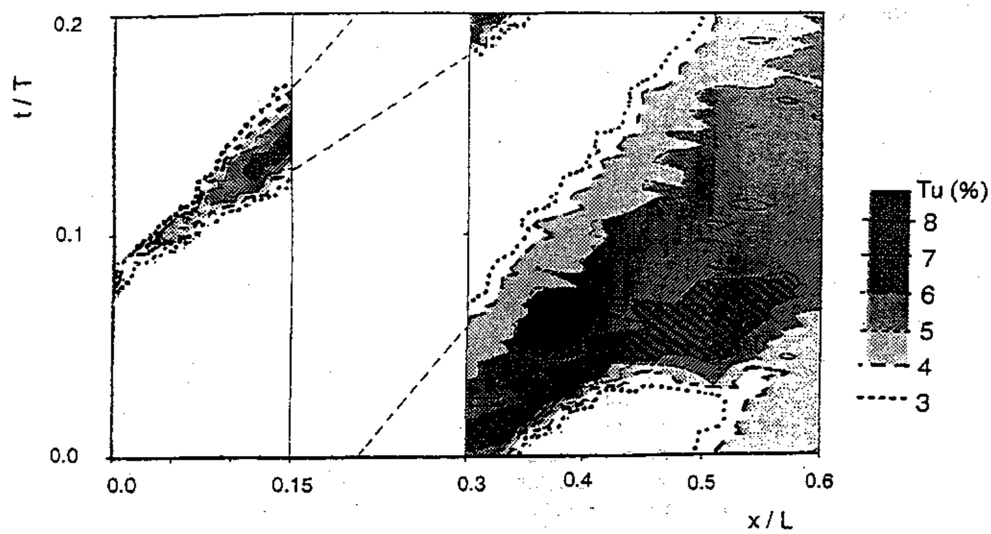

Fig. 6 The turbulent regions on the plane of $y/L = 0.2 \times 10^{-3}$ measured over the surface from to $x/L = 0.0$ to 0.15 and $x/L = 0.3$ to 0.6 (Case 5), show the evolution of the wake-induced turbulent patches

According to the present definition of wake duration τ_w as shown in Fig. 7, we can graphically determine values of the wake duration from the turbulence intensity contours obtained near the leading edge where the edges of the contours lie almost in parallel. In this case, the above-mentioned threshold for the wake-induced turbulent region is applied. Table 3 shows such values of the wake duration for three types of the wake-generating cylinders, in conjunction with the values presented in Part I. Although these values contain considerable uncertainty due to the somewhat rough estimation used here, the values agree with the experimental data. Relatively large discrepancy between the model and the experiment is seen for the 2 mm diameter case, probably because of the obscure edges of the turbulent region for that case. This comparison shows that the increasing trend of the wake duration for larger cylinder diameter, which has been incorporated in the transition model of Part I, is directly verified in this measurement.

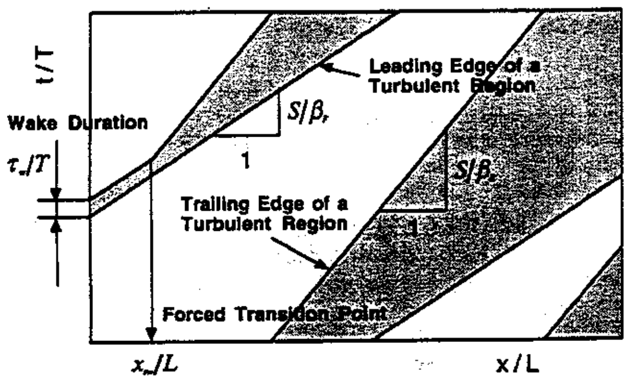

Fig. 7 An idealized state of the wake-affected boundary layer

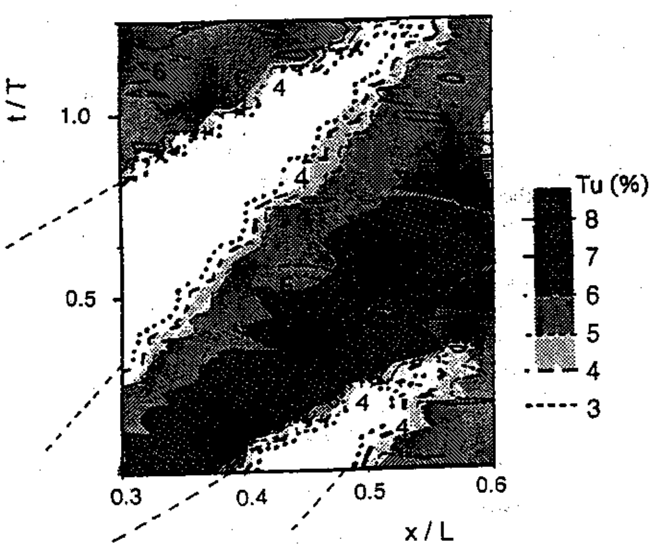

Fig. 8 The turbulent regions on the plane of $y/L = 0.2 \times 10^{-3}$ measured over the surface from $x/L = 0.3$ to 0.6 (case 6), showing the merger of the consecutive turbulent regions around $x/L = 0.5$

Table 2 Trailing edge propagation velocity ratio for each of the test conditions

d	Flow Condition	x/L	β_E
2	Case 1	0.3 - 0.6	0.54
2	Case 2	0.3 - 0.6	0.54
2	Case 3	0.3 - 0.6	0.55
2	Case 4	0.3 - 0.6	0.54
5	Case 1	0.3 - 0.6	0.50
5	Case 2	0.3 - 0.6	0.59
5	Case 3	0.3 - 0.6	0.52
10	Case 3	0.3 - 0.6	0.54
2	Case 5	0.3 - 0.6	0.53
5	Case 5	0.3 - 0.6	0.57
2	Case 5	0.0 - 0.15	0.53
5	Case 5	0.0 - 0.15	0.51
10	Case 5	0.0 - 0.15	0.59
2	Case 6	0.0 - 0.15	0.53
5	Case 6	0.0 - 0.15	-

Table 3 Wake duration (Measured and model values) (unit is ms)

	Wake duration	Model value
d = 2	0.48	0.15
d = 5	2.13	1.77
d = 10	3.96	3.40

Onset of the Wake-Induced Transition

Direct and Indirect Effects of the Wake Passing. Before discussing where wake-induced transition will start, it should be noted that some controversy recently arose among several researchers about the mechanism of the wake-induced transition. Dong and Cumpsty (1990) and Addison and Hodson (1990a, b, 1991) concluded that the wake turbulence was mainly responsible for the transition and any effect of velocity fluctuations associated with the wake passage on the transition was minimal. A similar concept was presented by Mayle and Dullenkopf (1990), stating that the wake was a production source of turbulent spots. On the contrary, Walker (1993), citing the data of compressor blade measurements, claimed that velocity fluctuations in the wake-induced transition process were important and held that turbulent spots evolved from the growth of "instability wave pockets," which tended to lag the wake passage. Meanwhile, the present study concludes that turbulent patches arise due to the passage of the periodic wakes, while finding no evidence for the appearance of the turbulent patches induced by the velocity fluctuations. Nevertheless, because of the limited number of data in this study, it is impossible to deny any possible roles of the wake-associated velocity fluctuation in the transition process.

According to Obremski and Fejer (1964), the effect of the velocity fluctuations can be characterized by a nonsteady Reynolds number Re_{NS}, which is defined as

$$\mathrm{Re}_{NS} = \frac{U}{\nu}\frac{\Delta U}{\omega} = \frac{UC}{\nu}\frac{U}{\omega C}\frac{\Delta U}{U} = \mathrm{Re}\,\frac{1}{k}\frac{\Delta U}{U}, \qquad (3)$$

where Re is a plate-length Reynolds number, k is a reduced wake-passing frequency, and ΔU is an amplitude of velocity fluctuation. They claimed that when Re_{NS} was less than 26,000, no transition due to the fluctuation occurred. In a high-pressure turbine stage of a typical aeroengine, on which the flow conditions in this study are based, one may find that $\mathrm{Re} \cong 10^6$, $k \cong 10^1$, and $\Delta U/U \cong 10^{-1}$, then $\mathrm{Re}_{NS} \cong 10^4$. In this sense, the effect of the velocity fluctuations can be discounted in the present cases. Accordingly, we hereafter regard the wake turbulence, rather than the velocity fluctuations, as a main cause of wake-induced transition.

Walker cited the observations by Orth (1992) as evidence of an indirect mechanism of wake passage, which was regarded as the counterpart of the direct action of the wake turbulence to induce a boundary layer transition. Before further discussion, the author would like to draw the readers' attention to the difference between wake generators used in the present study and in the experiment by Orth. He used a wake generator like a squirrel cage, in which several bars were horizontally installed so as to generate two-dimensional wakes behind them. This type of wake generator has some drawbacks; for example, it cannot help generating two different kinds of wake that were referred to as "near wake" and "far wake," respectively, by Orth. The near wake was generated when a bar in the wake generator passed just ahead of the plate leading edge and the far wake was generated when a bar moved at the far distance from the leading edge. In fact, existence of the far wake makes the simulated flow field more complicated. In addition, due to the structure of the wake generator, relative motions of the wake-generating bars to the inlet flow at the near and far positions differ. As a result, both the near and the far wakes impinge on the test plate in considerably different ways. In other words, the directions of wake-associated negative jets, whose existence was pointed out by Meyer (1957), are different for the near and the far wake cases, which makes the situation more complex and sometimes confusing. Accordingly, careful attention should be paid when using a squirrel cage as the wake generator.

Figure 9, which is a reproduction of one of the figures in Orth's paper, depicts contours of turbulence intensity obtained

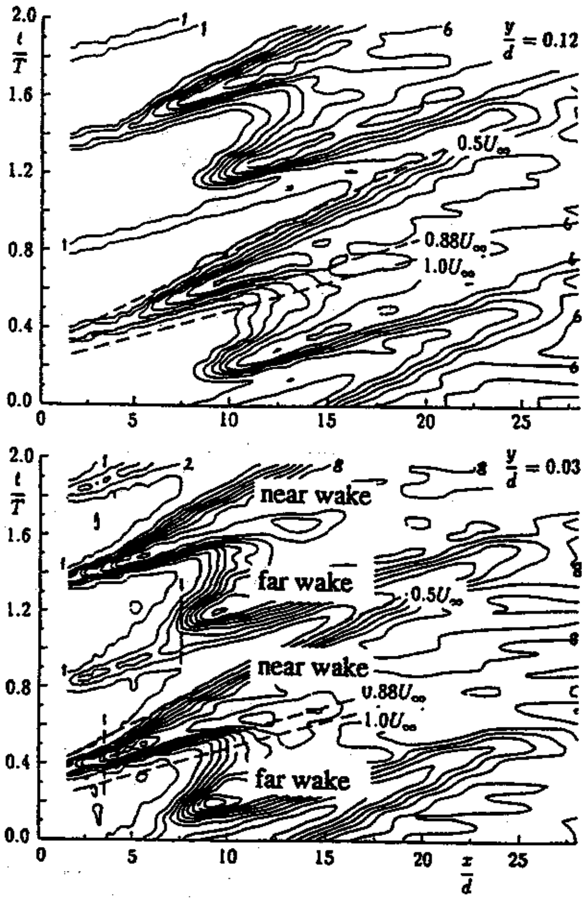

Fig. 9 Experimental data cited from Orth (1992), illustrating the evolution of the highly turbulent regions induced by the near and far wakes

on the plane nearest to the test surface as in the current Fig. 3. Note that the measurement location is at $y/L = 0.6 \times 10^{-3}$ according to this paper's notation. Orth stated in his paper that it is clear that the "near" wake affects the boundary layer so directly that it induces a turbulent patch immediately underneath. Walker pointed out, on the other hand, that the effect of the far wake appears to be somewhat restrictive and the wake seemingly has no direct connection with the turbulent patch appearing at $t/T \cong 1.2$ (see upper portion of Fig. 9). Considering the observed slow growth rate of the induced turbulent patch by the far wake ($l_D/L = 0.48$) as well as the fact that the measurement location of Fig. 9 is three times distanced from the test surface than that of the present case, however, it is quite likely that a turbulent patch is caused by a weak far wake but it is not detected while it grows under the measuring plane of $y/L = 0.6 \times 10^{-3}$. Consequently, the present author has come to believe the following story: The far wake in Orth's case affected the boundary layer directly and accordingly induced a turbulent patch underneath. However, its growth was slow compared to the near-wake case mainly because the low turbulence intensity involved and partly because of the direction of the far wake "negative" jet is opposite to that of the near wake.

Proposal of a New Model for Onset of the Transition. In the transition model proposed in Part I, the onset of the wake-induced transition was regarded as the point where the trailing edge of a wake-induced turbulent patch emerged from the preceding wake (x_{nw} in Fig. 14 of Part I), and the effect of the wake characteristics on that point was ignored. Through the present experiments, however, we have found that the situation is not so simple as in that model. For example, location of x_{nw} depends considerably on the wake characteristics as indicated in Table 4. These results show that some modification on the

Table 4 Comparison of the wake-induced transition point

	x/L (Exp.)	x/L (Model)
d=2	0.052	0.045
d=5	0.038	0.045
d=10	0.032	0.045

model is necessary, especially about the onset of the wake-induced transition.

Based on the findings in this study, a slightly modified transition model shown in Fig. 10 is developed. This new model assumes that one or more turbulent patches appear somewhere beneath a wake, whose locations depend on the wake turbulence intensity. Because of the short diffusion time scale of the wake turbulence into the boundary layer, it is possible to adopt a quasi-steady approach by use of the well-known natural transition criterion of Abu-Ghannam and Shaw (1980)

$$Re_\theta = 163 + \exp(6.91 - Tu), \tag{4}$$

in order to determine an onset location of the turbulence patch as Addison and Hodson (1990a, b) did. In this case, local turbulence intensity distribution within the wake is substituted into Tu of Eq. (4) for a free-stream turbulence intensity. Equation (4) implies that even in a highly turbulent wake case ($Tu \geq 6$ percent), no turbulent patch occurs before the position of Re = 163. This means $x_{tw}/L = 0.03$ in the present case. Note that this model does not guarantee any appearance of the wake-induced turbulent patch at the place that Eq. (4) specifies, but only provides a particularly possible position of the appearance of the turbulent patch beneath the wake. One might wonder if this method makes the estimation of the transition onset rather difficult because of its uncertainty about the position of the turbulent patch. As far as the growth of the turbulent region is concerned, however, it is not necessary to pay attention to all possible turbulent patches but only to those appearing after the peak of the turbulence intensity. When the wake is sufficiently intense, as shown schematically in the upper part of Fig. 10, it is quite likely that turbulent patches appear even at the rear portion of the wake center. It follows from this assumption that the wake-induced transition point in the "old" definition, x_{tw}, would be found near the limiting line of Re = 163 (x_{tw}/L = 0.03), which matches the situation for the 10 mm cylinder case in Table 4 ($x_{tw}/L = 0.032$). When the wake is weak, on the other hand, a limited number of turbulent patches arise around the wake center at the location marked with x_s. In that case, x_{tw} tends to be located a little downstream from x_s, which is determined by the following relationship:

$$x_{tw} = x_s + \frac{U_\infty \tau_w}{2\left(\frac{1}{\beta_E} - \frac{1}{\beta_F}\right)} = x_s + 0.61 U_\infty \tau_w. \tag{5}$$

Since a peak value of Tu for the 2 mm cylinder case was about 4 percent, combining Eq. (4) with Eq. (3) yields $x_{tw} = 0.046$, which is close to the corresponding value in Table 3 ($x_{tw} = 0.052$). Moreover, the peak value of Tu in the far wake case was 3 percent at most, which means that any turbulent patch initiates around $x/L \cong 0.05$, and is consistent with the result of Fig. 4.

Discussion

We have concentrated our attention on the wake turbulence intensity only, and no discussions are made about the effects of the other wake turbulence statistics, for instance the length scale of the wake turbulence or the Reynolds stress. O'Brien and Capp (1989), on the other hand, conducted unsteady flow measurements behind a spoke-wheel wake generator, which had the structure similar to that of the present study, and found that higher levels of Reynolds stress was obtained by the moving circular cylinders as compared to those measured behind an actual inlet guide vane. They concluded that the higher wake turbulence level could be responsible for the higher heat transfer measured in a cascade test case using the wake generator, as compared to the results of an actual rotating turbine stage. Their study accordingly indicates that further investigation is necessary about the effect of the wake turbulence characteristics on the transitional behavior of the wake-affected boundary layer.

As for a natural transition criterion, Mayle (1991) recently proposed another correlation as follows:

$$Re_\theta = 400\, Tu^{-5/9}, \tag{5}$$

where Tu is in percent. He claimed that his correlation yielded better results than the correlation of Abu-Ghannam and Shaw did, especially at high free-stream turbulence case. Using Eq. (5) instead of Eq. (4) seems to be one of the possible options, but care should be paid to the fact that the natural transition point given by Eq. (5) goes upward monotonously according to the free-stream turbulence. This is quite a contrast to that of Eq. (4), which yields the asymptotic value of the transition point. Therefore, further studies remain to be done about which is more suitable for the wake-induced transition problem.

Conclusions

Behavior of the wake-affected boundary layer on the flat plate is investigated in detail by hot-wire anemometry. Comparisons are then made between the results obtained and the wake-induced transition model proposed in Part I. Findings in this study are summarized as follows:

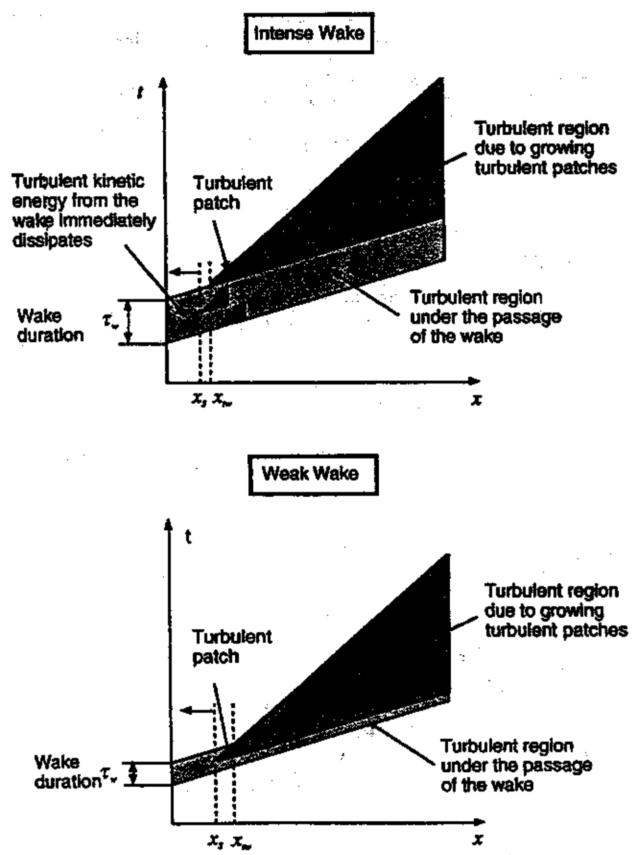

Fig. 10 A modified model for an onset of the wake-induced transition

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

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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_{rw}, 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 $\bar{f}$, i.e.,

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

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

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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.

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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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