Effects of Periodic Wake Passing upon Flat-Plate Boundary Layers 
Experiencing Favorable and Adverse Pressure Gradient

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ABSTRACT
This paper deals with the investigation of wake-disturbed boundary layer on a flat-plate model with an elliptic leading edge. The wakes are generated by the transversely moving bars in front of the test model. Main focus of this paper is on how the wake passage affects the transitional behavior of the boundary layer under the influence of favorable and adverse pressure gradients over the test surface. Detailed measurements of the boundary layer are conducted by use of a hot-wire anemometry. An ensemble-averaging technique is also employed in order to extract the periodic events associated with the wake passage from the acquired data. The previously observed dependence of wake-induced transition on the movement of the wake generating bar is confirmed. It is also found that the wake passage induces a significant change in the flow structure downstream of the flow acceleration region.

NOMENCLATURE
- \(d\) : diameter of the wake-generating bar
- \(C_p\) : pressure coefficient
- \(f\) : wake passing frequency
- \(H_{12}\) : shape factor
- \(K\) : acceleration parameter
- \(L\) : length of the test model
- \(n\) : rotation per minute
- \(n_s\) : number of wake-generating bars
- \(\text{Re}, \text{Re}_s\) : Reynolds number (= \(U_L/v\)), local Reynolds number (= \(U_s(x)/v\))
- \(S\) : Strouhal number
- \(\tilde{\tau}\) : wake-passing period
- \(\tilde{T}_u\) : ensemble-averaged turbulence intensity
- \(\tilde{T}_e\) : free-stream temperature
- \(t\) : time
- \(U_s(x)\) : free-stream velocity at the outer edge of the boundary layer
- \(U_i\) : inlet velocity

INTRODUCTION
A number of concerns have been raised about the unsteady-flow effect on the aerodynamic performance of rotor and/or stator cascades of axial turbomachines. For example, the deterioration in aerodynamic performance of a low-pressure turbine stage in commercial aero-engines, which is anticipated to occur when they operate under the cruise condition, could be reduced due to the existence of wake-blade interaction. Schulte and Hodson (1994)(1996) found from the inspection of the steady and wake-affected pressure distributions on the blade suction surface that upstream blade wakes suppressed a separation bubble which would otherwise occurred on the suction surface and deteriorated the cascade performance. Funazaki et al. (1997c) conducted measurements of stagnation pressure distributions downstream of a linear cascade of turbine blades that was subjected to periodic wakes from the upstream moving bars, and identified a slight reduction in the loss associated with the blade wake. Similar to the study of Schulte and Hodson, they concluded from the flow visualization that a separation bubble on the blade suction surface was diminished due to the wake-blade interaction. Halstead et al. (1995a)(1995b) investigated the wake-blade interaction phenomena in a large-scale compressor and turbine. Important studies related to separation bubble on a blade surface were also reported by several researchers (for example, Cumpsty et al. (1995),

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and/or free-stream turbulence. This paper describes the relevant interaction between the separation bubble and incoming periodic wakes.

Despite the above-mentioned studies, information is still lacking on the effects of free-stream turbulence and periodic wake passage upon the behavior of the separation bubble over a blade surface, which is important for the development of more efficient turbomachines. At the same time, such information is needed for verification of CFD codes as well as turbulence models that will be used in the aerodynamic design of turbomachines. This has driven the authors to start a research project which aims to gain quantitative data concerning the aerodynamic interaction between the separation bubble and incoming periodic wakes.

The test model used by Funazaki et al. (1997c) was emulated over the test surface. A spoked-wheel type wake generator was employed to generate incoming wakes. This study also examined the effect of the rotation direction of the wake generator on the aerodynamic interaction between the wakes and the boundary layer similar to the previous studies (Funazaki et al. 1997a, 1997b). Detailed hot-wire probe measurements were executed to obtain steady and wake-affected velocity data of the boundary layer.

TEST APPARATUS

Experimental Setup

Figure 1 shows a schematic layout of the test facility used in this study. The settling chamber and the contraction nozzle reduced free-stream turbulence from the blower down to about 0.8%. Incoming wakes were produced by a spoked-wheel type wake generator which was located upstream of the test model. The wake generator consisted of a disk with 400mm diameter and cylindrical bars of 5mm diameter. Revolution number of the disk in the wake generator was counted by the optical tachometer. The wake generator was set so that each of the wake generating bars became parallel with the leading edge of the test model when it moved in front of the model. The fluctuation in revolution was also monitored and it was found to be less than 0.5%. Figure 2 shows the test model and the passage-contouring device attached on the top wall of the test duct which was used to generate a specified pressure gradient on the surface of the test model. Also shown is the system for the boundary layer measurement. The test model made of acrylic-resin was 1.075 m length and had a semi-elliptic leading edge with the long axis of 75mm and the short axis of 15mm, followed by a flat-plate afterbody. The width and thickness were 200 mm and 30 mm, respectively. Static pressure taps were provided on one side of the test model to measure the pressure distribution imposed on the test surface. Stainless steel foils covered the other side of the model to measure wake-affected heat transfer on the surface, which was not reported in this study. The passage-contouring device was adjusted so as to reproduce the pressure distribution similar to that on the suction surface of the turbine blade which was investigated by Funazaki et al. (1997c). In order to avoid a biased inflow condition due to the asymmetric configuration of the test model with respect to the duct center line, a screen was attached to the lower exit of the test duct. The mesh size of the screen was selected so that the aerodynamic stagnation line almost matched the mechanical stagnation line, which was confirmed by the oil-flow pattern near the leading edge of the test model. The contouring device was equipped with a slot along its center line through which a hot-wire probe could be inserted into the main flow. The slot was securely plugged with several blocks to prevent the leakage from the slot.

Rotation direction of the disk in the wake generator was easily reversed, which changed the movement of the wake-generating bars relative to the test model, as designated 'normal rotation' or 'reverse rotation' in Figure 2. Funazaki et al. (1997a, 1997b) found through the previous studies that the relative movement of the bars and the associated fluid motion so-called negative jet seemed to have some effects on the transitional behavior of the wake-affected boundary layer. In those cases, however, since the leading edge of the test model used was sharp-edged, it could not be completely denied that the sharp-edged
leading edge affected the transitional behavior of the boundary layer through the temporal fluctuation of the flow incidence associated with the wake passing. Therefore, the present study was anticipated to yield another evidence for the negative-jet effect upon the wake/boundary layer interaction.

Instrumentation and Data Processing

A single hot-wire probe was used to measure the boundary layer on the test model. A PC-controlled traversing unit placed the probe to the location to be measured with the precision ±0.01 mm. The probe was connected to a constant temperature anemometer. By monitoring the free-stream temperature at the exit of the test section, the temperature unit effectively compensated the temperature fluctuation of relatively low frequency during the long-running measurement. A/D conversion of the linearized signal of the probe was initiated with the once-per-revolution signal from the optical tachometer, which guaranteed the application of the phase-locked averaging technique to the sampled data. Data sampling rate was 50 kHz and each of the digitized time-history records contained 2048 words. Accordingly, phase-locked or ensemble-averaged velocity, \( \bar{v} \), was calculated from the acquired instantaneous velocity data, \( v_k \) (\( k = 1, 2, 100 \)) as follows:

\[
\bar{v}(x, y, t) = \frac{1}{N} \sum_{k=1}^{N} v_k(x, y, t)
\]

Ensemble-averaged turbulence intensity was also defined by

\[
\bar{t}_u(x, y, t) = \frac{1}{U_e} \sqrt{\frac{1}{N-1} \sum_{k=1}^{N} (v_k(x, y, t) - \bar{v}(x, y, t))^2}.
\]

where \( U_e \) was the local velocity determined from the static pressure measurements with the Bernoulli's equation. From the ensemble-averaged velocity, boundary layer integral characteristics such as displacement thickness were calculated using the following equations:

\[
\bar{\delta}_d(x, t) = \int_0^1 \left( 1 - \frac{\bar{v}(x, y, t)}{U_e(x)} \right) dy.
\]

\[
\bar{\gamma}_d(x, t) = \int_0^1 \left( 1 - \left( \frac{\bar{v}(x, y, t)}{U_e(x)} \right)^2 \right) \bar{v}(x, y, t) dy.
\]

\( \bar{\delta} \) was an ensemble-averaged boundary layer thickness, which was the distance where the ensemble-averaged velocity reached the maximum among the data acquired at the same streamwise location. Shape factor was accordingly calculated by

\[
\bar{H}_{12}(x, t) = \bar{\delta}_d(x, t) / \bar{\delta}_d(x, t).
\]

Uncertainty

Uncertainties of the inlet velocity and instantaneous velocity measured were about 2% and 3%. It followed the integral characteristics given by Eqs. (3), (4), and (5) contained uncertainties of about 6%, 7%, and 8%, respectively. The shape factor defined by Eq. (6) accordingly had more or less 10% uncertainty.

RESULTS

Test Conditions

Wake-affected unsteady flow field around the test model was characterized by two non-dimensionalized numbers, i.e., Reynolds number \( Re \) and Strouhal number \( S \), defined by

\[
Re = \frac{U_s L}{\nu},
\]

\[
S = \frac{f L}{U_s},
\]

where \( U_s \) was inlet velocity and \( L \) was the length of the test model. In the present case \( U_s = 20 \text{ m/s} \), \( n = 1200 \text{ rpm} \), and \( n_b \) was 2 and 3, corresponding to \( Re = 1.43 \times 10^6 \) and \( S = 2.15 \) and 3.23, respectively. Inlet free-stream turbulence was about 0.8%.

Static Pressure Distribution

Figure 3 shows the pressure distribution on the suction surface of the turbine blade used by Funazaki et al. (1997c) and the measured static pressure distribution, with the calculated one by use of a potential flow analysis code based on BEM (Boundary Element Method) for comparison. Static pressure coefficient, \( C_p \), is calculated by

\[
C_p = \frac{p - p_{\infty}}{\frac{1}{2} \rho U_s^2} = \left( \frac{U_s}{U_{\infty}} \right)^2.
\]

Also shown is the corresponding acceleration parameter defined by the following equation:

\[
K = \frac{\nu}{U_s^2} \frac{dU_s}{dx}.
\]

It follows that the average acceleration parameter was about \( 0.8 \times 10^{-2} \) before the deceleration. Although a slight difference in the peak position of the pressure distribution, which originated from the mechanical restriction of the passage-counting device, was observed between the turbine blade and the present test model, the overall profiles of the pressure distributions was similar to each other. Figure

\[
\begin{align*}
\bar{\delta}_d(x, t) & = \int_0^1 \left( 1 - \frac{\bar{v}(x, y, t)}{U_e(x)} \right) dy, \\
\bar{\gamma}_d(x, t) & = \int_0^1 \left( 1 - \left( \frac{\bar{v}(x, y, t)}{U_e(x)} \right)^2 \right) \bar{v}(x, y, t) dy.
\end{align*}
\]
Figure 4 Raw velocity signals measured at $y = 0.2 \times 10^{-3}$ m for several locations over the test model in the case of no wake condition, showing the transitional behavior of the boundary layer under the influence of the pressure gradient.

Figure 5 Comparisons of displacement and momentum thicknesses between the measurement and the calculation using the boundary layer analysis code developed by Schmidt and Patankar (1991). This code, incorporated with Lam-Bremhorst two-equation turbulence model, contains a limiting function that suppresses an excessive growth of the production term in the
Figure 6. Raw velocity signals measured at \( y = 0.2 \times 10^{-3} \) m for several locations over the test model with the influence of the wake passing on the test surface \((S = 3.23)\), where the upper and lower data of each of the graph columns were acquired in the normal and reverse rotation cases, respectively.

The calculated results agreed with the experimental data only in the acceleration region up to \( x/L = 0.4 \), prior to the onset of transition.

Figure 6 also exhibits the raw data of the wake-affected velocity in the case of \( S = 3.23 \). Two diagrams are shown for each of the measurement locations, where an upper and a lower diagram present the data acquired in the normal and reverse rotation cases, respectively. As seen in the diagrams at the location 1, the most upstream measurement point, the wake passages in the normal and the reverse rotation cases induced quite different events on the test surface. The detected velocity decreased during the wake passing in the normal rotation case, while the velocity in the reverse rotation exhibited slight decrease followed by evident increase. This difference seems to be attributed to an effect of negative jet of the wake which impinges on the test surface in the normal rotation and leave the test surface in the reverse rotation in a relative frame of reference moving with the free-stream. Enlargement of the highly fluctuating regions was observed from the data at the

Figure 7. Numerical calculations of wake-compressor blade interaction executed by Valkov and Tan (1983)
Figure 8 Snapshots of the ensemble-averaged turbulence intensity contours of the wake-disturbed boundary layer experiencing favorable and adverse pressure gradients (S = 3.23 / Normal Rotation).

Locations 2, 3 and 4, indicating the progress in the wake-induced transition towards the downstream, however, the durations of those regions clearly differ between the normal and reverse rotation cases, as reported in the previous studies by Funazaki et al. (1997a)(1997b). Close inspections of the data revealed that the highly-fluctuating regions for the normal rotation case were likely to be accompanied by the significant decrease in velocity, while those regions for the reverse rotation showed only minor velocity decrease in the wake. In order to
Therefore one can conclude that the above-mentioned difference in the duration of the fluctuating region was mainly due to the effect of the wake migration from the suction surface. At the location 8 spike-like events were no longer observed and the boundary layer thereafter reached the turbulent state rather abruptly. This observation implies that the wake-induced transition mode dominated the transition process as a whole, resulting in fully turbulent state assisted by the adverse pressure gradient.

**Ensemble-Averaged Turbulence Intensity** For further investigation of the wake-affected boundary layer, ensemble-averaged turbulence intensity contours that represent bar-wakes interacting with the boundary layer are shown in Figure 8. This figure represents some of the sequential snapshots during one wake-passing period T for the case of the normal rotation with S=3.23. At the instant when one bar-wake, which was identifiable from its high turbulence intensity, reached the most upstream measuring position at \( T/T = 0.0 \), there was a clear evidence showing the appearance of wake-induced turbulence zone (turbulence patch) beneath the incoming wake. As the wake was convected downwards, the leading edge of the induced turbulence patch moved almost along with the wake while the trailing edge of the patch lagged behind the wake, resulting in gradual expansion of the turbulence patch in the streamwise direction. Due to the effect of the flow acceleration, however, the height of the patch remained almost unchanged. In the instant when the leading edge of the patch reached the trailing edge of the foregoing turbulence patch \( T/T = 0.4 \), another high turbulence region occurred at \( L = 0.45 - 0.5 \) (from location 4 to location 7) designated 'A', exhibiting quick growth in the y-direction (normal to the wall) due to the effect of adverse pressure gradient. A plausible explanation on this event was a high rate of turbulence spot generation at the decelerating flow regime (Mayle (1991)). The other cause was the interaction between the bar-wake and a separation bubble, on which further investigations are needed.

Figure 9 also shows the snapshots of the ensemble-averaged turbulence intensity contours for the reverse rotation with \( S=3.23 \). As seen in the raw data of Figure 5 or numerical calculation in Figure 7, the incoming wake moved away from the test surface so that the wake width (or wake duration) became narrow compared to that of the normal rotation case. Since contributions from the wake turbulence to the turbulence patch were minimal, the streamwise extent of the turbulence patch was also relatively limited. At the moment when the wake passed over the zone \( L = 0.45 - 0.5 \), a highly turbulent region designated 'B' appeared and grew likewise in the normal rotation case.

To enhance the understanding of the behaviors of the wake-induced turbulence patch observed in Figures 8 and 9, the corresponding distance-time diagrams of the wake-induced turbulence contours measured at \( y = 0.2 \) mm are shown in Figure 10 for the normal and reverse rotation cases. The turbulence patch exhibited a feature of evolution quite similar to the previous studies of Halstead et al. (1995a) or Funakaki et al. (1996b) in the acceleration region. A distinct difference in the time-wise extent of the turbulence patch were again confirmed between the both rotation cases. It was also evident that the transition process for the normal rotation case was dominated by the wake passage, while the inter-wake transition could be observed for the reverse rotation case. Recently much attention has been paid to the effect of calmed region on the separation bubble (Schule and Hodson (1997), for example). In Figure 10, however, the appearance of the calmed region was not clear, so that another contours of turbulence intensity were plotted for the lower Strouhal number case, \( S = 2.15 \), as shown in Figure 11. Regions of relatively low turbulence intensity, marked with 'C', occurred just behind the wake-induced turbulence patch and these could be regarded as calmed regions. The appearance of the low turbulence

**Figure 9** Snapshots of the ensemble-averaged turbulence intensity contours of the wake-disturbed boundary layer \( S=3.23 / \) Reverse Rotation

Examine these phenomena from the viewpoint of the negative jet effect, the numerical study done by Valkov and Tan (1993) was reviewed, who analyzed the wake-disturbed flow field around a compressor cascade by use of a Navier-Stokes solver. Figure 7 shows the disturbance flow vectors around the compressor blade, which were obtained by subtracting the calculated unsteady flow field from the corresponding steady flow field at two different instants. Speaking of the relation of their results to the present study, wakes on the blade suction or pressure surface seemingly corresponded to ones in the reverse rotation case or the normal rotation case in terms of the relative motion of the fluid inside the wake against the surface of concern. However, one should keep in mind that the pressure distribution on the compressor blade was quite different from the present case, which affected the boundary layer thickness. It was found that incoming wakes were deformed by the stagnant flow at the leading edge, resulting in the appearance of accelerated flow region following the wake as expected from the negative jet theory (see Figure 7(b)). In addition the incoming wakes on the suction surface tended to migrate away from the suction surface.
regions was also confirmed by comparing time-history records of turbulence intensity in the right-hand side of Figure 11, which were measured at three different locations near the area 'C'.

**Time-averaged shape factor and energy dissipation thickness** Figure 12 shows time-averaged shape factors for several unsteady flow conditions, which was defined by the integration of the ensemble-averaged shape factor over the wake-passing period as follows:

\[ H_{12}(x) = \frac{1}{T} \int_0^T \hat{H}_{12}(x,t) dt \, . \]  

(11)

It is actually difficult to draw a general conclusion from this figure because of its large uncertainty, however, the following findings can be stated. Firstly, the shape factor for no wake condition exhibited relatively high value over the zone ranging from \( x/L = 0.4 - 0.5 \), followed by sharp decrease indicating the onset of the boundary layer transition. This seems to be another evidence for the existence of the separation bubble that was mentioned above. Secondly, the wake-affected shape factor tended to decrease with the increase in Strouhal number, which was more pronounced in the normal rotation case for the same Strouhal number. Furthermore, the wake-affected shape factor for higher Strouhal number or normal rotation cases did not display any rise over the zone \( x/L = 0.4 - 0.5 \) in contrast with the no wake condition. This indicated that separation bubble was suppressed by the wake passage and the transition process was dominated by the aerodynamic interaction between the wake and the boundary layer experiencing the adverse pressure gradient.

Figure 12 shows time-averaged energy dissipation thickness distributions. As demonstrated by Denton (1993), energy dissipation thickness corresponds to entropy thickness or aerodynamic loss generation in the boundary layer. Although most of the measured data were of similar magnitude before \( x/L = 0.4 \), considerable differences were thereafter observed among the data. Despite some data scattering, a close inspection of this figure revealed that deviations of the wake-affected energy dissipation thickness from that of no wake condition gradually increased almost in a linear fashion along with \( x/L \) until the end of the flow acceleration. This corresponds to the behaviors of wake-induced turbulence regimes in the \( x-t \) diagrams in Figure 10, indicating little impact of the favorable pressure gradient upon the evolution of wake-induced turbulence patch. Significant increase in the energy dissipation thickness arose after \( x/L > 0.4 \), in particular for higher Strouhal number. No evidence could not be identified for loss reduction due to the wake passage.

As described earlier, the present study was motivated by the cascade test of Funazaki et al. (1997c). However, the present study could not fully reproduce the flow conditions of their previous study due to some mechanical restriction of the test facility. For example, free-stream turbulence intensity in the present study was slightly higher than that of the cascade test (about 0.5%). Furthermore Reynolds number was much higher and the effect of curvature was ignored in this case. These differences were partly the reason for smaller separation bubble
e.g., aerodynamic loss as seen in Figure 13. This is consistent with the contribution of the separation bubble to the energy dissipation thickness.

CONCLUSIONS

The findings in this study can be itemized as follows:

1. From raw data and/or ensemble-averaged data of wake-disturbed velocity inside the boundary layer, a prominent difference was identified between the normal and reverse rotation likewise in the previous study using the sharp-edged flat plate. This was also confirmed by the distance-time diagrams of turbulence intensity.

2. Wake-induced turbulence patch exhibited an abrupt growth at the instance when its leading edge reached the decelerating flow region, and the boundary layer thereafter became fully turbulent suppressing the steady-state transition mode.

3. The appearance of calmed regions just behind the wake-induced turbulence patches was observed in the distance-time contours of turbulence intensity.

4. The time-averaged shape factor indicated that the separation bubble was suppressed by the wake passage and the transition process was dominated by the aerodynamic interaction between the wake and the boundary layer, in particular for high Strouhal number.

5. The time-averaged energy dissipation thickness linearly increased in the accelerating region on the test model.

6. No evidence could not be identified for loss reduction due to the suppression of the separation bubble by the wake passage, partly because of the high Reynolds number flow in the present study.

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REFERENCES