STUDIES ON TURBULENCE STRUCTURE OF BOUNDARY LAYERS DISTURBED BY MOVING WAKES

K. Funazaki and Y. Aoyama
Iwate University
Morioka, Japan

ABSTRACT

An attempt is made to measure wake-affected boundary layers on a flat plate by means of a split-film probe. Although a number of studies have been made to reveal the transitional behavior of boundary layers subjected to periodic wake passing, much is still unknown on the turbulence structure of those boundary layers. It is because most of the studies measured the boundary layers by single hot-wire probe. This measurement therefore aims at the determination of the turbulent structure of the incoming wakes as well as the disturbed boundary layers mainly in terms of ensemble-averaged Reynolds shear stress and turbulence intensity. Unsteady velocity vectors associated with the wakes and wake-induced turbulence patch (a number of turbulent spots) are also determined in detail. In comparison to a conventional hot-wire probe, the probe used in this study is less sensitive to fluctuations of high frequency and less accurate in the near-wall measurement due to its relatively large diameter of its sensor. However, new and important information is obtained on the structure of wake-induced turbulence patch, which provides more insight into the wake-induced boundary layer transition than before. In addition, the measured velocity field following the turbulent patch indicates a clear image of calmed region.

NOMENCLATURE

- $A_i, B_i$: constants of sensor (i)
- $b_{12}$: semi-depth width of bar wake
- $d$: diameter of wake-generating bar
- $E_i$: voltage output from sensor (i)
- $f_i(\theta)$: a function of flow angle for sensor (i)
- $n_i$: constant (power) of sensor (i)
- $R_i$: resistance of sensor (i)
- $T$: wake-passing period
- $t$: time
- $T\bar{u}(t)$: ensemble-averaged turbulence intensity
- $U_e$: velocity at the outer edge of boundary layer
- $U(t)$: velocity magnitude
- $u(t), v(t)$: streamwise and transverse velocity components
- $\bar{u}'v'(t)$: ensemble-averaged Reynolds shear stress
- $x$: longitudinal distance from the leading edge of the model
- $X_d$: distance between the bar and the model leading edge
- $y$: distance from the surface of the test model
- $\delta_{99}$: boundary layer thickness
- $\nu$: kinematic viscosity
- $\theta(t)$: flow angle

superscript

- $\bar{\cdot}$: ensemble-averaged value
- $-\cdot$: time-averaged value
- $'\cdot$: fluctuation measured from the average

INTRODUCTION

Boundary layer transition induced by periodic wakes moving over airfoils in axial-turbomachines has been attracting much attention from various fields of researches during the last two decades, and a large amount of information on the wake-induced transition is now being compiled, mostly from experimental activities, into a database (For example, Chakka and Schobeiri (1999), Kittichaikarn et al. (1999), Kim and Crawford (1999), Funazaki and Koyabu (1999), as relevant and recent studies). Despite these efforts, because of the utilization of unidirectional probes or surface sensors in the experiments, only limited knowledge is available on turbulence structure of the wake-affected boundary layers. Therefore, to the authors' best knowledge, very few studies have been done to clarify time-resolved Reynolds stress distributions within the boundary layers or the structure of a wake-induced turbulent patch, clustered turbulent spots, in detail. Let us briefly discuss on this turbulent patch. Figure 1 is a schematic expression of the turbulent patch given by Hodson et al. (1992). This figure gives us an idea on how turbulent spots are generated under the wake, however, the situation is not as simple as depicted in Figure 1. Some studies (Makita and Nishizawa (1998)(1999)) using two small pulse jets have revealed that interaction between two identical and neighboring turbulent spots changed the growth pattern of each of the tur-

Figure 1  Schematic of turbulent patch under a wake (Hodson et al. (1992))
bulent spots in comparison with that of an isolated turbulent spot. The interaction became more complicated when the turbulent spots did not emerge simultaneously. From these experiments using only two turbulent spots, one can easily imagine that a number of turbulent spots must be interacting with each other in a very complex manner under the wake, then characterize the resultant turbulent patch and eventually affect transitional behavior of wake-disturbed boundary layer. This indicates the importance of exploring the structure of wake-induced turbulent patch for better understanding of boundary layer transition in turbomachines.

This study was the authors’ first attempt to conduct two-component velocity measurements using a split-film probe upon transitional boundary layers on a flat plate which were subjected to periodic wake passage, aiming at the clarification of the structure of the wake-affected boundary layer. The split-film probe was employed for the boundary layer measurements in consideration of its small size which enabled it possible to be positioned close to a wall (Bruun (1995)).

**EXPERIMENTS**

**Test Apparatus**

Figure 2 shows the test section and the measuring system. The test model, which was already used in the study of Funazaki and Koyabu (1999), had an elliptic leading edge of 75 mm long axis and 15 mm short axis, followed by two flat plates. The total streamwise length of the model was about 1000 mm and the span was 200 mm wide. Moving bars on the rotating disk generated periodic wakes that impinged the model surface. The bar diameter $d$ was 5 mm. While the streamwise distance between the wake-generating bar and the model leading edge $X_n$ was usually 300 mm, this distance was changed in a case to examine the effect of the wake turbulence intensity on the transition of the boundary layer. Revolution direction of the disk could be reversed, which changed the interaction between the wake and the boundary layer through so-called negative jet effect (Funazaki et al. (1997a)). An optical tachometer detected the disk rotational speed.

Two-channel Constant-Temperature-Anemometry system (Kanomax model 1010) was used for the velocity measurement, where a temperature compensation unit (Kanomax model 1020) measured the free-stream temperature as shown in Figure 2. A PC-controlled digitizer (Autonics APC-204) acquired all three analog signals from the system with 50kHz sampling frequency. The optical tachometer generated a pulse per revolution that triggered the data acquisition. A traverse unit placed the split-film probe, whose detail will be given in the following, to a specified point within the accuracy of 0.05 mm.

**Split-Film Probe**

**Measurement Principle** Figure 2 also shows the split-film probe used for the boundary layer measurements (TSI Model 1287). The sensing part of this probe is a small crystal-fiber rod of 0.15 mm diameter, on which two electrically insulated thin films are deposited as sensor. The principle of two-dimensional velocity measurement by means of the split-film probe is as follows.

Suppose that each of the outputs from the sensing films can be expressed as the product of two functions of flow velocity $U$ and flow angle $\theta$, respectively, we have a following expression (Bruun (1995)).

$$E_i^2 = \left( A_i + B_i U N \right) \tilde{f}_i(\theta) \left( T_s - T_a \right), \quad (1)$$

where $E_i$: output from the sensor, $R_i$: operational resistance of the sensor, $T_s$: sensor temperature, $T_a$: ambient temperature, $A_i$, $B_i$, $i = 1, 2$.

Substitution of Eq. (2) into Eq. (1) yields the following equation,

$$\frac{E_i^2}{R_i} = \left( \tilde{A}_i + \tilde{B}_i U N \right) f_i(\theta) \left( T_s - T_a \right), \quad (3)$$

where $a_i^{(1)} \tilde{A}_i = \tilde{A}_i$, $a_i^{(2)} \tilde{B}_i = \tilde{B}_i$. When $\theta = 0$ in Eq. (3), we have

$$\frac{E_i^2}{R_i} |_{\theta = 0} = \left( \tilde{A}_i + \tilde{B}_i U N \right) \left( T_s - T_a \right). \quad (4)$$

Calibration using the above equation provides the sensor constants $\tilde{A}_i$, $\tilde{B}_i$, $n_i$. The function $f_i(\theta)$ is also experimentally determined from the following equation,

$$f_i(\theta) = E_i^2 \left( T_s - T_a \right) |_{\theta = 0} \left/ \frac{E_i^2}{R_i} |_{\theta = 0} \left( T_s - T_a \right) \right. \quad (5)$$

Eliminating $\theta$ from Eqs. (3) for $i = 1$ and $i = 2$, the following equation for the velocity $U$ is derived as

$$\tilde{B}_1 \tilde{B}_2 \left[ 1 - \frac{a_1}{a_2} \right] U N_2 + \tilde{A}_2 \tilde{B}_2 \left( 1 - \frac{a_2}{a_1} \right) = \tilde{A}_1 \tilde{B}_1 - \tilde{B}_1 e^{2 \frac{E_i^2}{R_i}} U N_2.$$
The flow angle \( \theta \), Reynolds shear \( \tau \), uncertainty \( \pm 2\% \) accuracy. The voltage outputs from the two sensors estimated \( \pm 0.078 \) for the regular cause by the uncertainty of the expressions in Eq. (1). Then the probe holder pitchwisely tilted the probe in order to determine the angular function \( f_i(\theta) \) in Eq. (5). Due to a mechanical constraint of the holder, the probe inclined by \( \pm 25^\circ \). Two output signals and the jet temperature were simultaneously obtained using the above-mentioned measurement system.

Figure 4 demonstrates an example set of the experimentally determined angular function \( f_i(\theta) \) and \( f_2(\theta) \) for the sensor 1 and sensor 2, respectively. This graph revealed that the both function linearly varied with \( \theta \) within the range tested, as expected in the above.

Operation One thing we had to pay attention to was the thermal interaction between the two heated films. To avoid this, the operational resistance of each of the films was selected so that the sensor temperatures were kept equal to each other.

Data Reduction Ensemble-averaged velocity components \( \vec{u}(\theta), \vec{v}(\theta), \) and turbulence intensity \( \hat{T}(\theta) \) were calculated from the records \( U_k(\theta) \) and \( \theta_k(\theta) \) \( k = 1, \ldots, m \), \( m = 128 \) as follows:

\[
\vec{u}(\theta) = 1/m \sum_{k=1}^{m} U_k(\theta) \cos \theta_k(\theta), \quad \vec{v}(\theta) = 1/m \sum_{k=1}^{m} U_k(\theta) \sin \theta_k(\theta),
\]

\[
\hat{T}(\theta) = \left[ \frac{1}{m} \sum_{k=1}^{m} \left( U_k(\theta)^2 + 2\vec{u}(\theta) \vec{v}(\theta) \right) \right]^{1/2} / U_{in},
\]

where \( U_k(\theta) = u_k(\theta) - \bar{u}(\theta) \) and \( v_k(\theta) = v_k(\theta) - \vec{v}(\theta) \). Reynolds shear stress was also defined in an ensemble-average fashion as

\[
\vec{u}' \vec{v}'(\theta) = \frac{1}{m} \sum_{k=1}^{m} U_k(\theta) v_k(\theta).
\]

Flow Conditions and Measurement Points Inlet flow velocity \( U_{in} \) was 20 m/s and the background turbulence level was about 0.8 %. When using a turbulence grid, the turbulence level slightly increased up to 1.2 %. Test conditions for the measurements of wake-disturbed boundary layers are listed in Table 1. The most upstream measurement point was at \( x = 0.078 \) for the regular configuration of the test model, i.e., \( X_j/d = 60 \). The measurement points at each of the streamwise locations located over the zone extending from \( y = 0.2 \text{ mm} \) to \( y = 15 \text{ mm}, \) clustering near the surface. Two wake-generating bars were attached on the rim of the disk rotating at 1200 rpm in the present case, which led to the bar speed of about 45 m/s at the mean radius of the bar. The resultant unsteady flow fluctuated at the wake-passing frequency of 40 Hz.

Uncertainty Analysis Uncertainty associated with the velocity measurement by use of the split-film probe seemed to consist of two major parts: calibration error and error arising from the probe itself. The calibration error affected the uncertainty of the velocity magnitude \( U \) through the empirical constants such as \( n_i \) in Eq. (6). Some numerical investigations revealed that the error in \( U \) caused by the uncertainty of the empirical constants was about 2.5 %. The angular error in \( \theta \) estimated from Eq. (3) was about 3.5 %.

As for the error caused by the probe itself, it has been realized that the greatest uncertainty of the split-film probe originates from its complex thermal response (Bruin (1995)) and, similar to any other hot-film probes, the split-film probe suffers from its poor frequency-response characteristics in comparison with hot-wire probes. In that sense it was important to understand how the split-film probe followed the unsteady flow caused by the wake passing for clarification of the uncertainty. However, it was actually a difficult task to make such an...
estimation rigorously. A simple approach taken in this study to measure the probe frequency response was to compare the data obtained with the split-film probe with those acquired with a proven technology, i.e., a single hot-wire probe. Figure 5 shows a comparison of ensemble-averaged velocity data obtained using the two different methods. It seemed that the velocity deficit of the split-film probe became about 5% smaller than that of the hot-wire probe, however, the both data almost coincided with each other, which might be thanks to relatively low frequency of the velocity fluctuation caused by the wake. This implies that the split-film probe was able to respond to the velocity fluctuation encountered in the present study as fast as a hot-wire probe, at least in the ensemble-average sense.

RESULTS

Velocity Distribution over the Test Model

Since there were no pressure holes on the test model, the velocity distribution over the model was analytically evaluated from a potential flow code. Figure 6 is the calculated velocity distribution, showing that the velocity rapidly accelerated nearby the leading edge, followed by a gradual decrease. Boundary layer analyses revealed that no separation was expected on the model, which was also verified by the oil-flow visualization in the preliminary test.

Steady Flow Measurements

Wake Profile Measurements To check the soundness of the probe and the above-mentioned procedure for determining velocity and flow angle, bar wake measurements were conducted with one of the wake-generating bars being placed horizontally along with the duct center plane. Note that the test model located at the far downstream of the test duct and the split-film probe was at 300 mm behind the bar. Figure 7 shows the measured distribution of time-averaged Reynolds shear stress inside the stationary wake normalized with the square of velocity defect, in comparison with the theory of Schobeiri et al. (1996). The experimental data almost matched the theory, however, there arose some discrepancies over the region $y/b_{1/2} = 0.0 - 1.0$, which were attributed to slight vertical non-uniformity of the mean flow inside the duct.

Flat-Plate Boundary Layer Measurements Figure 8 shows a streamwise velocity profiles at $x = 0.15$ and $x = 0.25$ on the test model for no grid condition. Also shown is the Blasius solution, where

$\eta$ was defined as

$$\eta = \chi \sqrt{U_e/\nu_x}.$$  \hspace{1cm} (10)

Most of the measured data at $x = 0.15$ followed the Blasius solution except for the data obtained very close to the surface. These discrepancies occurred where $\eta < 1.5$, which corresponded to about $y < 0.5$ mm. This indicates that the data obtained near the wall ($y < 0.5$ mm) were less accurate. The data at $x = 0.25$ exhibited a slight deviation from the Blasius solution, suggesting the onset of boundary layer transition around there. Figure 9 presents the velocity traces acquired at $x = 0.25$ and $x = 0.30$ for several transverse locations from the surface. One can notice the appearance of ‘wave packet’-like patterns in the near-wall traces, which eventually evolved to be a turbulent spot as seen in the traces for $x = 0.30$. Figure 10 displays boundary layer...
Figure 8  Velocity profiles measured at x = 0.15 (left) and x = 0.25 (right) for no grid condition, with Blasius solution

Figure 9  Traces of streamwise velocity component measured at x = 0.25 (left) and x = 0.30 (right) for no grid condition

thicknesses measured for low (no grid) and moderate (with grid) free-stream turbulence conditions, accompanied with calculated laminar boundary layer thickness. The measured data for the no grid condition deviated from the calculation from x = 0.4, which almost corresponded to the observations of the velocity traces mentioned above.

Unsteady Flow Measurements
Case 1 - Baseline Measurements - Figures 11 and 12 exhibit contours of ensemble-averaged turbulence intensity and Reynolds shear stress measured at several streamwise locations, respectively, where the abscissa is the elapsed time from the trigger point and the ordinate is the distance from the test surface. The turbulence intensity contours in Figure 11 indicated the incoming wakes on the test model as well as the turbulence spots growing beneath the wakes. One can spot the occurrence of a zone with relatively high turbulence intensity, i.e., turbulent patch, at x = 0.078, which grew in the cross-flow and streamwise directions. Since the value of the Reynolds shear stress sinusoidally varied with time in the free-stream away from the test surface, the turbulent patch observed in Figure 11 could be identified much clearer in Figure 12 as negative value zone of \( \bar{u}' \bar{v}'(t) \) under the wake. This intense shear zone, taking the shape of iceberg, dominated the near-wall region beneath the wake. This turbulent patch moved with the wake, its height and length being enlarging. It was also found that the Reynolds shear stress tended to have relatively large magnitude at the front portion of the turbulent patch.

To examine the flow structure near the wake and the wake-induced turbulent patch in more detail, the wake-perturbed velocity field from which the time-averaged velocity field was extracted was superimposed on the Reynolds shear stress contours at x = 0.15 and x = 0.30 as seen in Figure 13. Note that a velocity vector directed to the
right means a decrease in velocity. It is clear that the incoming wake for the normal rotation case first induced velocity increase, which was followed by the decrease in the velocity. A close inspection of the velocity vectors revealed that the perturbed velocity vectors inside the wake had the velocity components towards the test surface, which was marked with the circle D in the upper of Figure 13. These phenomena were due to the negative jet effect of the wakes. Inside the turbulent patch that followed the wake, marked with the circle A, the wake-affected velocity field exhibited considerable deceleration in comparison to the time-averaged velocity field. The accelerating zone marked with the circle C, which seemed to correspond to a calmed region, then appeared after the precedent intense shear zone near the
Figure 13  Time-resolved Reynolds shear stress contours measured at x = 0.15 (upper) and x = 0.30 (lower), with velocity vectors induced by the wake and the turbulent patch (case 1).

Some discussions are necessary on turbulent patch. As mentioned earlier in this paper, the authors defined that the turbulent patch was a cluster of turbulent spots randomly generated under the wake, as depicted in Figure 1. Unfortunately it was not possible to distinguish one turbulent spot from others inside the turbulent patch, however, it seems useful to compare the structure of the measured turbulent patch with that of a well-documented turbulent spot for the discussion described in the following. Figure 14 shows a typical streamwise perturbation velocity field associated with a turbulent spot, which was reported by Makita and Nishizawa (1998). Note that this spot was created by pulse air injection from a small hole. Also shown in Figure 13 is the streamwise perturbation velocity field of the turbulent patch, where the ordinate is the distance normalized with the steady bound-

test surface. Similar statements can be applied to the data at x = 0.30, except for the facts that the wake-induced intense shear zone as seen in the circle E as well as the subsequent flow-accelerated region designated with the circle F significantly grew while they moved from x = 0.15 to x = 0.30. The other point to be mentioned on these contours is positive value zones of \( \bar{u}' \bar{v}'(t) \) occurring under the leading and trailing edges of the turbulent patch. Although the near-wall flow measurements by use of the split-film probe was likely to contain large errors, it appears that these zones had some physical meanings in connection with the wake-affected flow field and the resultant turbulent patch. In addition, it is evident that the near-wall vectors beneath the turbulent patch marked with circle A or E had upward velocity components.
ary layer thickness. In general, the features of the both streamwise perturbation velocity fields resemble each other in terms of the appearance of the velocity deceleration, followed by the acceleration, i.e., calmed region. In addition, the bottom of each of the deceleration zones located around $y/\delta = 0.5$. On the other hand, one can also identify some differences. For example, the bottom of the deceleration zone of the turbulent patch was considerably flat and large in comparison to that of the turbulent spot. One plausible explanation for this difference was the effect of several turbulent spots coexisting or being merged in the turbulent patch. It also seemed convincing that the negative jet effect contributed to the difference, however, much remains unknown yet.

**Case 2 - Effects of Decayed Wake** - Figures 15 demonstrates Reynolds shear stress contours and streamwise perturbation velocity contours obtained for the case 2; the axial distance between the moving bar and the test model enlarged by 200 mm. Again the ordinates are normalized with the steady boundary layer thicknesses, respectively, while the upper limit of the measured areas are all the same (8 mm). Note that the boundary layer measurement near the leading edge became enabled in this case. Due to this enlargement, the peak value of the wake turbulence $Tu_{max}$ decreased from 5% down to 4%. It appears that the occurrence of turbulent patch under the wake could not be clearly observed at least until $x = 0.075$. This was a contrast to the data for the case 1, meaning delay of the wake-induced transition. The shear stress contour at $x = 0.10$ provides a clear image of a growing
Case 3 - Effect of the Direction of the Bar Movement - Figures 16 and 17 display contours of ensemble-averaged turbulence intensity and Reynolds shear stress measured at several locations for the reverse rotation case. Comparisons of these contours with those in Figures 11 and 12 reveals that the wake duration for the reverse rotation case
became shorter and shorter as it moved downstream. Accordingly, wake-induced turbulent patches gradually lagged behind the preceding wakes, lastly separated each other. This was quite in contrast to the normal rotation case (case 1). Impacts of the bar movement direction upon the wake-induced transition were first reported by Funazaki and his colleagues (1996)(1997a), and reconfirmed by Kittichaikarn et al. (1999). Figure 18 explains the separation between the wake and the turbulent patch more clearly, where ensemble-averaged Reynolds shear stress contours at $x = 0.15$ and $x = 0.30$ for the reverse rotation case were shown along with their perturbed velocity vectors. The turbulent patch was characterized as the intense shear stress zone as well as decelerated zone. The perturbation velocity vectors exhibited several interesting features to note. Due to the upward fluid motion inside the wake (positive jet effect), the vectors beside the wake, as marked with A and B, were directed toward the wake. These movements consequently induced the flow that went beyond the turbulent patch from the backside of the patch as indicated in the circle B for $x = 0.15$ or in the circles D and E. Upward vectors underneath the turbulent patch were again observed as seen in the circle C or F likewise in the case 1 measurements (see Figure 19 as the close-up of the right-side contours in Figure 12 for the sake of a direct comparison with Figure 18).

A comparison between Figure 18 and Figure 19 yields that the wake-induced turbulent patch for the normal rotation seemed larger than that of the reverse rotation. It could be possible to image that the incoming wake of the normal rotation contributed to this difference through generating turbulent spots under the front portion of the wake. Otherwise, as indicated by Kittichaikarn et al. (1999), broadly-distributed virtual origins of the turbulent spot had some influences on the difference in growth rate of the turbulent patch, although further studies are still necessary to verify these suppositions.

**Case 4 - Effect of Free-Stream Turbulence** - Figure 20 shows the ensemble-averaged Reynolds shear stress contours and the perturbed velocity vectors for the case using the turbulence grid, where the wake-generating bar moved in the normal direction. Due to the enhanced free-stream turbulence, the level of the background shear stress increased. Comparing the contour and the velocity vectors with those of the case 1 (or Figure 19), the size of the turbulent patch became smaller and the shear stress level in the patch was considerably low for the case 4. In addition, the upward movement under the patch was calmed down. It is also evident that the front side of the wake bent in the thickened boundary layer, as seen in the circle A. These changes seemed to be related to the production rate of the turbulent spots. Finally one can notice the appearance of a small dip of the shear stress as well as

![Figure 18](image18.png)

Figure 18 Reynolds shear stress contours at $x = 0.15$ (left) and $x = 0.30$ (right), with velocity vectors (case 3)

![Figure 19](image19.png)

Figure 19 Close-up of Reynolds shear stress contours and perturbation velocity vectors at $x = 0.30$ (case 1)

![Figure 20](image20.png)

Figure 20 Close-up of Reynolds shear stress contours and perturbation velocity vectors at $x = 0.30$ (case 4)
the acceleration zone behind the turbulent patch marked with the circle B. Again this indicates the existence of the calmed region.

**Discussion**

In the last section of this paper, the authors discuss the development of the calmed region following the wake-induced turbulent patch. The existence of the calmed region was identified in the perturbation velocity data as shown in Figure 14, however, it seems useful to check the calmed region from another point of view, such as in terms of Reynolds shear stress. Figure 21 shows Reynolds shear stress at y=0.5mm for the case 1 displayed on x-time diagram, where the regions with negative value of the Reynolds shear stress are depicted with shaded region and those with positive Reynolds shear stress are marked with lines. Also shown are the three straight lines that represent trajectories of the fluid particles moving at 100%, 55% and 30% free-stream velocity over the flat plate, $U_e (=22 \text{m/s})$, respectively. The front of the negative value region moved almost along with the free-stream and the rear of the region moved much slower. These features matched those of turbulent spots, as indicated by Halstead et al. (1997). The other point to be noted here is the appearance of the positive Reynolds shear stress behind the wake-induced turbulent patch. It is clear that the rear end of the positive Reynolds shear stress regions moved almost at 30% free-stream velocity, which corresponded to the rear end speed of calmed region (Halstead et al. (1997)). In addition, according to the study of Wang and Keller (1999), non-turbulent motion of the transitional boundary layer contributed to the appearance of positive Reynolds shear stress in the boundary layer. These findings therefore implies a possibility that the positive value regions were strongly related to the calmed region, although further studies are needed to verify it. Figure 22 represents that the wake-affected turbulence intensity measured at y=0.5mm (case 1) on x-time diagram, with contours of the positive Reynolds shear stress. The behavior of the highly turbulent regions resembled that of turbulent spots, similar to the negative Reynolds shear region. Since the positive shear stress appeared over the regions of low turbulence intensity on the x-time diagram, it seems that those regions were not in ‘true turbulence’ state but were caused by the fluctuation of the non-turbulent (irrotational) flow of the boundary layer.

**CONCLUSIONS**

This study aimed at clarifying the turbulent structure of the wake-affected boundary layers at several flow conditions by the measurement of the flow field including wakes using the split-film probe. A new procedure was developed to calculate two velocity components from the two signals of the probe, whose validity was verified in this study to some extent. Despite the shortcoming of the probe especially in the very near-wall measurements, the probe successfully, and seemingly for the first time, revealed time-resolved two-dimensional fluid motions around the wake and its induced turbulent patch. At the same time, the authors believe that the measurements helped the readers to grasp the evolutional process of the wake-induced turbulent patch more vividly by looking at the ensemble-averaged Reynolds shear stress in the flow field. Although the coverage of the measurements was far from satisfaction for extraction of any decisive conclusions, major findings in the present study, which are itemized in the following, provide an insight into this complicated flow event.

(1) The structure of the measured turbulent patch resembled a single turbulent spot generated by pulse air injection to some extent, how-
ever, the bottom of the decelerated zone associated with the turbulent patch extended larger than that of the turbulent spot.

(2) As previously reported in several literatures, separation of the wake from the following turbulent patch was confirmed again in the reverse rotation case. The detected velocity vectors also indicated positive jet-like fluid motion near the wake, while the negative jet effect was observed in the normal rotation case. These relative motion near the wake seemed to affect the structure of the turbulent patch.

(3) Under the enhanced free-stream turbulence case the measured turbulent patch was smaller and exhibited relatively low level of Reynolds shear stress inside.

(4) Ensemble-averaged Reynolds shear stress could be a useful index to identify the development of the wake-induced turbulent patches as well as the calmed regions behind the patches.

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REFERENCES


