ABSTRACT

This study deals with extensive hot-wire probe measurements of wake-affected separation bubble on the leading edge of a test model. The purpose of the study is to investigate time-resolved response of the separation bubble to incoming wake passage. Another focus is placed on the wake effect on aerodynamic loss generated in the separated boundary layer, seeking any relationship between the suppression of the separation bubble on a cascade airfoil and aerodynamic gain due to the clocking in turbomachines. The test model has a semi-circular leading edge and two flat-plates. Incoming wakes are generated by circular cylinders which are horizontally fixed in the wake generator. Several types of wake generating cylinders are used in order to change wake properties. The hot-wire measurements have revealed the time-resolved responses of the separated boundary layer to the wake passage. Effects of calmed regions just behind the moving wakes are also identified.

INTRODUCTION

A number of studies have been made on unsteady flow effects upon separated boundary layers or separation bubbles on the suction side of turbine blades. Several researchers, namely, Addison and Dong [1], Dong and Cumpty [2], Schulte and Hodson [3], Kaszeta, Simon and Aspis [4], examined wake-separation interaction phenomena, using linear cascades and wake generators. The purpose of those studies was mainly for seeking how and to what extent blade loading can be increased without any severe separation on blade suction surface by taking advantage of wakes passing over the surface. Lou and Hourmouziadis [5] documented transitional behaviors of separation bubbles on a flat plate subjected to main flow fluctuations, where a pressure gradient over the flat plate was imposed using a contoured wall. A similar study was made by Volino and Hultgren [6], focusing on the effect of free-stream turbulence upon the separation bubble.

In contrast, fewer studies have been made on the investigation of periodic wakes affecting leading edge separation bubble on a compressor blade, while several studies have been made on steady-state separation bubbles on the blade leading edge [7], [8], [9]. Paxson and Mayle [10] measured wake-affected velocity profiles of the boundary layer on the leading edge of a blunt test model. Funazaki et al. [11], followed by Funazaki and Kato [12], using a test mode similar to that of Paxson and Mayle, examined the interaction between a stationary wake from an upstream bar and separated boundary layer on the test model with semi-circular leading edge. They changed the vertical position of the wake generating bar, aiming at the emulation of so-called clocking in a compressor. It was accordingly found that aerodynamic loss associated with the separated boundary layer could be reduced to some extent by a proper choice of the bar position. These studies successfully provided important insights into the clocking mechanism, however, further studies on periodic wake passing over the test model were also needed for better understanding of the clocking effects likewise in the study by Walker et al. [13]. Aiming at deepening our understanding of the clocking mechanism in turbomachines, this paper describes several important results from hot-wire probe measurements of the wake-affected separation bubble on the same test model as that previously used by the authors. Incoming wakes were generated by circular cylinders which were horizontally fixed on the timing belts of the wake generator. Several types of wake generating cylinders were used in order to change wake properties.

NOMENCLATURE

- $d$: bar diameter
- $f_{bp}$: bar-passing frequency
- $H_{12}$: shape factor
- $L$: loss generated in the boundary layer
- $R$: radius of the leading edge of the test model
- $Re$: Reynolds number ($= U_{in} R / \nu$)
- $t$: time
- $T$: averaging time length
- $T_{bp}$: bar-passing period
- $U_{in}$: inlet velocity
- $U_{max}$: maximum velocity attained near the surface
- $U_{up}$: reference velocity measured at $y = 50$mm
- $u_k$: $\bar{u}$: raw velocity data, ensemble-averaged velocity
- $x_i$: distance along the surface from the leading edge
- $Y$: vertical distance from the center line of the test model
- $y$: vertical distance from the test model surface
- $y_{bar}$: vertical shift of wake generating bar from the center line
- $y_{max}$: height where the maximum velocity $U_{max}$ appeared
- $\nu$: kinematic viscosity
- $\delta_1, \delta_2, \delta_3$: ensemble-averaged displacement, momentum and energy-dissipation thickness
- $\bar{\delta}_1, \bar{\delta}_2, \bar{\delta}_3$: time-averaged displacement, momentum and energy-dissipation thickness
superscript $\bar{\phi}$ : time-averaged and ensemble-averaged values of $\phi$

EXPERIMENTAL APPARATUS

Test Facility

Fig. 1 shows the experimental setup used in this study. Air from the blower passed through the wake generator before entering the test section. Fig. 2 displays the detail of the wake generator. It was almost the same as that used by Holland and Evans [14], and functionally similar to a squirrel-cage type wake generator used in the study of Orth [15] or Liu and Rodi [16]. The wake generator used in this study was superior to a spoked wheel type of wake generator used by Funazaki et al. [17] in terms of two-dimensionality of the wakes produced behind the moving bars. The wake generator consisted of two long timing belts, four geared pulleys and cylindrical stainless-steel bars, and it was fixed to the nozzle exit with four arms. The bars were attached to the belts horizontally using connecting profiles on the belt surface. The profiles were tightly glued on the belt surface with equal spacing of 63.5 mm, meaning that the bar pitch was a multiple of this profile pitch. Three types of the bars with different diameters, i.e., 3 mm, 6 mm and 9 mm were used to change wake characteristics. The induction motor was able to drive the belts at an arbitrary speed up to 10 m/s via the transmission. The bar moving direction was also changeable. Any bar in the wake generator passed across the main flow at two streamwisely different locations, where the distance between the upstream and downstream loci of the bars was about 300 mm. Consequently, the bar generated two different types of wakes during one rotation of the belt. In the following those wakes will be referred to as ‘upstream wake’ and ‘downstream wake’ according to the streamwise location of the bar locus.

Fig. 3 shows the test model. The model had a semi-circular leading edge with the radius of 100 mm (= $R$), accompanied by two flat plates. The length and width of the model were 900 mm and 280 mm, respectively. Two fences of 1 mm thickness and 10 mm height were attached to the test model at a height of 10 mm from each of the side walls of the duct. They were for minimizing any unfavorable effects of side-wall boundary layers upon the two-dimensionality of the flow around the test. The model was located 245 mm downstream of the nearest locus of the moving bars. A Pitot tube placed in front of the test section monitored the inlet velocity, using a pressure transducer of high precision.

Fig. 4 Coordinate system and measurement region
was also evaluated by 2]. The total number of the wake-generating bars for the range, was 0.095. Thus the bar wake nomi-

Data Acquisition

Fig. 3 also depicts two miniature hot-wire probes (Dantec 55P11 with 5 μm wire diameter and 1.25mm wire length) and one thermometer in the duct. The upper hot-wire probe was to measure the flow over the test model and the lower probe, called the wake probe, was to detect the arrival of the wakes from the bars. This wake probe was distanced from the downstream bar locus by 30 mm. Both probes were connected to CTA unit (Dantec Streamline) that was fully controlled by a PC. Outputs of the hot-wire probes, which were compensated to the flow temperature fluctuation, were simultaneously transformed from analog to digital by a built-in A/D converter (National Instruments AT-MIO-16E-1). The sampling frequency was 10kHz, and the sampled data number in one realization was 216. Dantec Streamware 1.14 controlled almost all procedures needed for the measurements, including probe traversing and calibration. The calibration was conducted for the velocity range from 0 - 15 m/s, and the resultant velocity - voltage relationship was approximated by a polynomial of 4-th order within about 1% accuracy.

Fig. 4 demonstrates the coordinate system and the measurement region adopted in this study. The measurement region extended streamwisely from $x/R = 0.96$ ($55^\circ$ from the center line) to $x/R = 4.57$, and vertically from $y/R = 0.3 \times 10^{-2}$ to $y/R = 0.5$. Great attention was paid to the accurate positioning of the probe, in particular near the surface of the test model using a precise height gauge as a guide to the specified height from the surface. It should be also noted that even in the measurement above the circular arc the probe was traversed along the vertical direction, not along the normal direction to the surface. Therefore, it was anticipated that estimations of boundary layer integral parameters described in the following would suffer some loss of accuracy over that region, especially near the leading edge.

Test Conditions

Inlet velocity $U_{in}$ was 10 m/s, giving Reynolds number $Re$ based on the radius of the model leading edge and the inlet velocity was $6.67 \times 10^4$. The total number of the wake-generating bars for the present study was 5, and the bar pitch was 635 mm. The bar moved at a velocity of 6m/s in the present study, above which the belts in the wake generator gradually exhibited vibration. The bar passing frequency $f_{bp}$ was then 9.5 Hz, and its wake-passing Strouhal number $St$, defined by $St = f_{bp}R/U_{in}$, was 0.095. Thus the bar wake nominally hit the test model with the wake angle of $31^\circ$ measured from the model axis as shown in Fig. 3.

Data Processing

Ensemble-Average Quantities

The wake probe detected the periodic arrival of the wakes from the bars, as shown in Fig. 5. As mentioned above, the wake generator produced two types of wakes and this figure clearly depicts the appearance of upstream and downstream wakes in the signal. It follows that the upstream wakes became weaker than the downstream wakes at the measurement plane due to the larger distance between the upstream locus of the bars and the wake probe. Taking advantage of the periodicity of the wake arrival, the authors calculated any ensemble-average quantities from each of the realizations such as shown in Fig. 5. In this case, one realization contained more than 60 downstream wakes. Using 50 segments from the velocity data, each of which was the velocity data during one bar passing period $T_{bp}$ (= 0.105 sec), the ensemble-averaged velocity $\bar{u}$ was calculated by

$$\bar{u}(x,y;t) = \frac{1}{N} \sum_{k=1}^{N} u_k(x,y;t), \quad N = 50.$$  \hspace{1cm} (1)

Ensemble-averaged turbulence intensity $\bar{T}u$ was also evaluated by

$$\bar{T}u(x,y;t) = \frac{1}{N} \sum_{k=1}^{N} [u_k(x,y;t) - \bar{u}(x,y;t)]^2 / U_{up}.$$  \hspace{1cm} (2)
was the velocity obtained at the upper limit of the measurement region, i.e., \( y/R = 0.5 \). Note that the above definition of the turbulence intensity inevitably included the contribution from non-synchronized fluctuations of the separation bubble, which might have affected the span of the highly turbulent region.

Boundary layer integral parameters were then calculated using the ensemble-averaged velocity as follows:

\[
\tilde{\delta}_1(x,t) = \int_0^{\gamma_\text{max}(x,t)} \left( 1 - \frac{\tilde{u}(x,t)}{U_{\text{max}}(x,t)} \right) dy,
\]

\[
\tilde{\delta}_2(x,t) = \int_0^{\gamma_\text{max}(x,t)} \frac{\tilde{u}(x,t)}{U_{\text{max}}(x,t)} \left( 1 - \frac{\tilde{u}(x,t)}{U_{\text{max}}(x,t)} \right) dy,
\]

\[
\tilde{\delta}_3(x,t) = \int_0^{\gamma_\text{max}(x,t)} \frac{\tilde{u}(x,t)}{U_{\text{max}}(x,t)} \left( 1 - \left( \frac{\tilde{u}(x,t)}{U_{\text{max}}(x,t)} \right)^2 \right) dy,
\]

where \( \tilde{\delta}_1, \tilde{\delta}_2 \) and \( \tilde{\delta}_3 \) were ensemble-averaged displacement thickness, momentum thickness and energy-dissipation thickness, respectively. \( \gamma_\text{max} \) was the location where the velocity measured along the vertical direction reached the maximum, \( U_{\text{max}} \), in the vicinity of the test model surface.

*Time-Averaged Quantities* It is common to use one bar-passing period as time-wise extent over which periodically fluctuating quantities are integrated to calculate the corresponding time-averaged values. In the present case, however, the velocity data inevitably contained the effects of the upstream wakes. Since the interest of the present study was only in the effects of the downstream wake upon the separated boundary layer over the test model, a series of the velocity data for about two-thirds of the bar-passing period were used, attempting to eliminate the effects of the upstream wake from the evaluation of the time-averaged boundary layer integral parameters. For example, time-averaged energy-dissipation thickness \( \tilde{\delta}_3 \) was obtained by

\[
\tilde{\delta}_3(x,y) = \frac{1}{T} \int_{t_0}^{t_0+T} \tilde{\delta}_3(x,y;t) dt,
\]

where \( T \) was the averaging time length and was 0.066 sec in this study. Using this time-averaged energy-dissipation thickness, an index of loss generation in the wake-affected boundary layer or the energy loss coefficient was defined by

\[
L = \left( \frac{\tilde{\delta}_3 U_{\text{max}}^3}{R U_{\text{in}}^3} \right).
\]

**RESULTS**

**Steady Flow Measurements**

Fig. 6 exhibits contours of velocity and turbulence intensity measured in the steady flow condition (or no wake condition), with a white broken line indicating the center of shear layer. Note that these contours were generated by the data obtained on the sub-domain region near the surface which consisted of 40 and 25 measurement points in the vertical and streamwise directions, respectively. The velocity data were normalized by \( U_{\text{up}} \). From the fact that the appearance of almost stagnant region or lift-off of the shear layer from the surface, it is clear that separation bubble started at \( x/R = 1.5 \) and reattached around at \( x/R = 2.0 \). It was also found from the comparison between the velocity contours and turbulence intensity distributions that the iso-velocity line having the value of 0.5 almost corresponded to the center of the shear layer, i.e., the local peak position of the turbulence. Fig. 7 represents several integral parameters of the steady-state boundary layer. The displacement thickness and the shape factor increased...
sharply until $x_{c}/R=1.7$, followed by rapid decrease lasting up to $x_{c}/R=2.0$. The shape factor became about 1.5 at $x_{c}/R=2.0$, implying that the boundary layer was in a turbulent state at the reattachment point. The momentum thickness exhibited a prominent increase in the separation region, thereafter it grew gradually almost in parallel to the displacement thickness.

Unsteady Flow Measurements

Time-resolved behaviors of the separated boundary layer Fig. 8 displays time-resolved velocity and turbulence intensities of the down-
stream wake measured at the 50mm upstream of the leading edge or 145mm downstream of the locus of the wake generating bars, where the abscissa represents time normalized by the wake passing period \( T \). Wake turbulence reached almost 16% and velocity deficit became more than 25% of the free-stream velocity for \( d = 9\) mm, while peak value of the wake turbulence was about 8% and the velocity defect was around 10% of the free-stream velocity for \( d = 3\) mm. It was also found that wake durations for \( d = 9\) mm, 6mm and 3mm were about 10%, 8% and 6% of \( T \), respectively, where the wake duration was defined as the time length over when the wake turbulence intensity remained more than 4% (Funazaki et al. [17]).

Fig. 9 exhibits several sequential snapshots of the turbulence intensity distributions superimposed by iso-velocity lines around the separation bubble that was subjected to the wake passing for \( d = 9\) mm. The broken lines in iso-velocity lines are the location where the normalized velocity was 0.5. These lines clearly indicate the responses of the separation bubble to the wake passing.

The separation bubble experienced almost no influence of the wake until \( t/T = 0.1 \) in Fig. 9. Thereafter the shear layer began descending towards the test surface even before the arrival of the downstream wake (\( t/T = 0.2 \)). The highly turbulent zone associated with the shear layer kept descending and shrinking at \( t/T = 0.25 \) and reached the minimum in the zone size and intensity when the incoming wakes covered the separation bubble at \( t/T = 0.3 \). It appears that the wake had swept off the separation bubble by \( t/T = 0.35 \). Thereafter the boundary layer entered the recovery phase, showing the gradual lift-off of the shear layer (\( t/T = 0.40 \) and later). This recovery process almost completed by \( t/T = 0.6 \). Roughly speaking, the separation bubble experienced the direct and indirect influences of the incoming wake from \( t/T = 0.2 \) to \( t/T = 0.6 \). This meant that the effects of the wake passing lasted about 40% of the wake passing period, which was much longer than that expected from the wake duration for \( d = 9\) mm. In fact, close inspections of the data revealed that the observed behaviors preceding the arrival of the downstream wake were due to the effects of the upstream wake. The upstream wake considerably weakened before it reached the measurement region, however it also broadened its width, eventually affecting the separation bubble prior to the downstream wake. Fig. 10 depicts timewise variations of normalized velocity and turbulence intensity distributions on two different cutting planes, i.e., \( x_s/R = 1.785 \) and \( y/R = 0.004 \). The wake is clearly seen in the velocity contours on \( y\)-time plane. In the turbulence intensity contours several noticeable zones appeared, which are denoted A, B and C. Zone A resulted from the effects of the upstream wake, as mentioned above. In zone B, just after the downstream wake, there occurred the enlargement of the turbulent area. This enlargement could be attributed to the emergence of the wake-induced turbo-

**Fig. 10** Variations of velocity (upper) and turbulence intensity (lower) on the two time-space planes (d = 9mm)

**Fig. 11** Evolution of highly turbulent region behind the wake (d = 9mm)

**Fig. 12** Variations of turbulence intensity on the \( x_s\)-time plane of \( y = 0.4\) mm, with the fluid particle traces moving at 100%,50% and 30% speed of the freestream (d = 9mm)
lent spots. In fact, as seen in Fig. 11, the highly turbulent region marked by “HT” grew behind the wake, which was followed by less turbulent region marked by “LT”. The high turbulence intensity area denoted C appeared beneath and after the downstream wake. Further investigation was carried out on zone C in order to find any correlation between the shape of the zone and the phenomena associated with the turbulent spots. Fig. 12 shows the turbulence intensity contours on the $x_s$-time plane, in conjunction with three traces of fluid particles moving at 100%, 50% and 30% of $U_{up}(x_s)$. The following relation was used to draw the 100% speed trace,
The starting point \( (x_0, t_0) \) on the \( x_s \)-time plane was chosen so that the 100% speed trace fitted the forefront of the highly turbulent zone, then drawing the 50% and 30% speed traces that lagged behind the 100% trace by the wake duration for \( d = 9 \text{mm}, \text{i.e., } 0.1T \). The 30% speed trace almost matched the rear end of the highly turbulent zone. This finding, in conjunction with the observation in Fig. 11, implies that a calmed region appeared behind the wake. For the verification of this supposition, Fig. 13 shows velocity contours on three the \( x_s \)-time planes, i.e., \( y=0.4\text{mm}, 0.6\text{mm} \) and \( 0.8\text{mm} \). These contours demonstrates that the low velocity region associated with the separation bubble tended to recover from the wake-affected state after the 30% speed traces. It can be stated from the discussions above that the incoming wake for \( d = 9\text{mm} \), accompanied by turbulent spots and the subsequent calmed region, swept over the separation bubble, preventing the boundary layer from getting separated.

Fig. 14 depicts timewise variations of normalized velocity and turbulence intensity distributions for \( d = 6\text{mm} \). Except for slightly weakened effects of the downstream wake, almost the same statements on the interaction between the separation bubble and the wake can be applied to this case. Fig. 15 also shows timewise variations of turbulence intensity for \( d = 3\text{mm} \). Due to the smallest wake turbulence intensity among the three, the shear layer was in effect unaffected by the wake, remaining detached from the surface. The starting point \( (x_0, t_0) \) on the \( x_s \)-time plane was chosen so that the 100% speed trace fitted the forefront of the highly turbulent zone, then drawing the 50% and 30% speed traces that lagged behind the 100% trace by the wake duration for \( d = 9\text{mm}, \text{i.e., } 0.1T \). The 30% speed trace almost matched the rear end of the highly turbulent zone. This finding, in conjunction with the observation in Fig. 11, implies that a calmed region appeared behind the wake. For the verification of this supposition, Fig. 13 shows velocity contours on three the \( x_s \)-time planes, i.e., \( y=0.4\text{mm}, 0.6\text{mm} \) and \( 0.8\text{mm} \). These contours demonstrates that the low velocity region associated with the separation bubble tended to recover from the wake-affected state after the 30% speed traces. It can be stated from the discussions above that the incoming wake for \( d = 9\text{mm} \), accompanied by turbulent spots and the subsequent calmed region, swept over the separation bubble, preventing the boundary layer from getting separated.

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surface during the wake passage.

(2) The emergence of wake-induced turbulence spot, followed by the resultant calmed region, were observed behind the downstream wake through the detailed examination of the contours of the time-resolved turbulence intensity as well as the velocity. They all worked as the separation suppression, i.e., they prevented the boundary layer from getting separated.

(3) Noticeable reduction of the energy loss associated with the separated boundary layer was achieved by the incoming wakes of $d = 9\text{mm}$ and $d = 6\text{mm}$.

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