PARAMETRIC STUDIES ON AERODYNAMIC PERFORMANCE OF VARIOUS TYPES OF LP TURBINE AIRFOILS FOR AERO-ENGINES UNDER THE INFLUENCE OF PERIODIC WAKES AND FREESTream TURBULENCE

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ABSTRACT

This study carries out parametric investigations on aerodynamic loss of various types of LP turbine airfoils characterized with different flow deceleration rates (DR) on their suction surfaces under the realistic flow conditions such as wake inflow and freestream turbulence. The Reynolds number examined in this study ranges from 57,000 to 170,000. As for the freestream turbulence, two levels of the turbulence are used, i.e., about 1.2% and 3.5%. Stagnation pressure distributions downstream of each of the airfoil cascades are measured by use of a Pitot tube, while steady-state and unsteady boundary-layers are measured over the rear part of suction surface and pressure side near the trailing edge using a single hot-wire probe. The measured boundary-layer data are used to estimate the cascade loss along with RANS (Reynolds-Averaged Navier-Stokes) simulations by taking advantage of the momentum-theory based Denton’s method. First, relationships between the cascade loss for each flow condition and DR are examined. The estimated loss values are then compared with the measured cascade loss to check the validity of the loss estimation method, which is a derivative of Denton’s method, under the realistic flow conditions.

NOMENCLATURE

- $t, t_{bar}$: cascade pitch, bar pitch
- $t_{TE}$: trailing edge thickness
- $u(y_{l})$: velocity profile of boundary layer
- $U_{bar}$: bar speed
- $U_{max}$: maximum velocity on the suction surface
- $U_{TE}$: velocity near the trailing edge (suction side)
- $U'$: axial velocity
- $U_{a}$: averaged exit velocity from the cascade
- $w$: throat length ($= t \cos \beta$)
- $y$: pitchwise direction
- $y_{a}$: height-wise coordinate normal to the surface
- $y_{bl}$: boundary-layer thickness
- $Y_{w}$: stagnation pressure loss coefficient
- $Z_{w}$: Zweifel loading factor
- $\beta_{1}, \beta_{2}$: inlet and outlet flow angles
- $\delta$: displacement thickness
- $\phi$: flow coefficient
- $\theta$: momentum thickness
- $\rho$: density
- $\nu$: kinematic viscosity
- $\sigma$: solidity ($= C_{s}/t$)
- $\zeta_{10}$: Denton-type cascade loss coefficient
- $\zeta_{11}$: measured cascade loss coefficient

Abbreviation

- PS, SS : pressure surface, suction surface
- R57 : condition at Re= 57,000
- R10 : condition at Re=100,000
- R17 : condition at Re=170,000
- TE : trailing edge

Subscript

- 1, 2 : inlet, outlet
- TE : trailing edge

Superscript

- $f$: mass-averaged value of quantity $f$
INTRODUCTION

Since most of the thrust from civil aero-engines with high-bypass ratio is produced by fan blades, low-pressure turbine (LPT) stages are required to generate huge power enough for driving the fan blades. Each of the LPT stages is composed of a large number of stators and rotors to maintain the high efficiency of LPT stages, however the total weight of LPT section is also a serious problem because it directly affects the fuel burn of airplanes. Reduction of the blade count in each of the stages is one way to lessen the LPT weight, which inevitably requires the increase in aerodynamic loading of LPT airfoils. Highly loaded airfoils or high-lift airfoils are likely to suffer from drastic increase in profile loss mainly due to the occurrence of large-scale boundary-layer separation or separation bubble on the airfoil suction surface when they operate at a cruise (low Reynolds number) condition. Therefore, aerodynamic designers of high-lift LPT airfoils are required to have better understandings of the profile loss characteristics of their airfoils against operational Reynolds numbers. It is well known that the profile loss characteristics are affected by various aerodynamic factors such as Reynolds number, periodic wakes shed from upstream airfoils, freestream turbulence in addition to several geometrical information of the airfoils including cascade solidity, the leading and trailing edge diameters, stagger angle, surface roughness and so on. Accordingly, a number of studies have been made on a wide variety of high-lift LPT airfoils to examine their profile loss characteristics under the influences of incoming wakes and freestream turbulence [1]-[8]. In addition to those efforts, several trials have been made to elaborate a correlation by which the designers may be able to make a loss estimation of the boundary layer loss influenced by separation bubble, wake passing and freestream turbulence. These trials are based on the method proposed by Denton [9], which revealed that the profile loss can be composed of three major contributors, i.e., boundary layer displacement thickness plus the trailing edge thickness (blockage effect), momentum thickness (mixing effect) and base pressure behind the trailing edge. Coull et al. [10] carried out comprehensive investigations on flat plate boundary layers with various pressure distributions under the influences of periodic wakes and/or freestream turbulence. Using those experimental data, they derived the correlation to predict the profile loss of high-lift LPT airfoils subjected to incoming wakes and freestream turbulence [11]. Although these studies are very valuable in designing highly efficient high-lift LPT airfoils, the authors believe that there are still other design spaces that were not dealt with in the above-mentioned studies but are indispensable for attaining high-lift LPT airfoils that can exhibit excellent performance on efficiency under a wide range of operating conditions.

Based on this idea, as the first trial to develop a method for designing high-lift LPT airfoils with high efficiency under realistic flow conditions, the present authors executed parametric investigations on aerodynamic loss of various types LPT airfoils with different flow deceleration rates (DR) on their suction surfaces without incoming wake condition [12][13]. They found in this study that a loss estimation method derived from the Denton’s method matched the cascade loss measured by use of the pneumatic probe within an acceptable range. Moreover, a close relationship was found between the cascade loss and the development of the suction surface boundary layer, indicating that the suction surface boundary layer was the most dominant contributor to the cascade loss and its impact to the total loss increased with DR.

The present study is then aimed at parametric investigations on aerodynamic loss of the LPT airfoils examined in the previous study [13] under incoming wake as well as elevated freestream turbulence conditions, while the Reynolds numbers examined were the same as those of [13]. A Pitot tube was used to measure the stagnation pressure loss of the cascades and a single hot-wire probe was employed to make unsteady boundary-layer measurements over the rear part of the suction surface in addition to the measurements on the pressure surface near the trailing edge. The obtained cascade losses are directly compared with the corresponding loss estimations using a derivative of Denton’s equation supplemented with numerical simulations. Several pieces of information useful for expanding the design space of LPT airfoils are obtained in this study.

EXPERIMENTAL METHODS

Since detailed information on the experimental method employed in this study was already reported in the previous work [12][13], only a brief explanation on how the measurements were carried out will be shown in the following.
Test Facilities

The test apparatus used in this study is shown in Figure 1. It is a low-speed wind tunnel, consisting mainly of a blower, settling chamber, wake generator and test section. A flow rate was controlled with the valve attached to the blower intake. The acrylic-resin duct was attached to the exit of the contraction nozzle of the wind tunnel, where a turbulence grid was installed to change freestream turbulence. The main flow temperature was monitored in front of the test cascade to calculate the air properties and to compensate the output from the hot-wire probe.

This study employed 6 different types of test cascades. Figure 2 shows one of the test cascades, which consisted of 7 airfoils. All test airfoils were machined from aluminum and brass ingots with the same axial chord length (100mm) and the span length (254mm). For each cascade a pair of brass airfoils were equipped with static pressure taps for the measurement of static pressure distributions on the suction and pressure surfaces. Each of the airfoils was fixed in the cascade with two plates on both airfoil ends. The airfoils at the middle of the cascade, numbered with 3, 4 and 5 in Figure 2, were target airfoils for the stagnation pressure measurement. Cascade periodicity along the pitchwise direction was confirmed through the measurement of stagnation pressure distributions downstream of the target airfoils after the adjustment of downstream guide plates of the cascade section.

Wake Generator and Turbulence Grid

The wake generator was installed just upstream of the cascade as seen in Figure 3 to emulate a realistic engine condition containing incoming wakes. It was comprised of cylindrical bars of 3mm in diameter, two timing belts driven by an electric motor. The bar diameter was chosen because it was close to the size of trailing edge of testes airfoils. The flow field disturbed by the wakes was characterized by the Strouhal number St, non-dimensional wake-passing frequency, which was defined by the actual chord length and inlet flow velocity, i.e.,

\[
St = \frac{f_{\text{bar}} C}{U_1} = \frac{U_{\text{bar}}}{t_{\text{bar}} U_1} = \frac{U_{\text{bar}}}{U_{1}/\cos\beta_1} = \frac{\cos\beta_1}{\phi} \frac{C}{t_{\text{bar}}}
\]

A turbulence grid was used to elevate the freestream turbulence intensity (FSTI) from about 1.2% to 3.5%. The grid consisted of cylindrical rods of 3.2mm in diameter, whose mesh geometry was 30mm x 30mm square. The grid was installed in parallel to the cascade 600 mm upstream of the center airfoil of the cascade.

Measurements by pneumatic probes

Miniature Pitot tubes (Tsukuba Rika Seiki Co.), whose head diameter was 3 mm, were used to measure an inlet stagnation pressure 30% Cx upstream of the cascade leading edge and the outlet stagnation pressure 15% Cx downstream of the cascade trailing edge. The position of the Pitot tube for the cascade downstream measurement was changed in the pitchwise direction by the PC-controlled traversing unit, where the probe head was carefully aligned with the design outlet flow angle of each of the test cascades. Since the dynamic pressure of the outlet flow was small, especially for the low Reynolds number condition, three different types of pressure transducers (Setra Systems Co. Model 265) with about 0.25% error of each full scale were selected according to the Reynolds number examined in order to maintain the measurement precision. The outputs from the transducers were acquired and digitized by the AD conversion board (Interface Inc.) and stored in PC. The static pressure measurement on the equipped airfoils was also made in a similar manner with the stagnation pressure measurement.

Measurements by hot-wire probe

The boundary-layer measurement on the airfoil surface was made using a single hot-wire probe (MODEL 55 P 11, Dantec Dynamics) with a constant temperature anemometer system (CTA; Kanomax Co.), where the output from the hot-wire probe was compensated by the monitored main flow temperature. The CTA output was captured by a data-logger (Keyence Wave Logger).
Figure 4 shows an example of the measurement grid spots, where around 10 axial locations were selected over the suction surface. The most upstream location varied from airfoil to airfoil, depending on probe accessibility and static pressure distribution. Velocities at 32 points in total for each axial location were measured along the normal line to the surface, starting from yφ=0.2mm to 9.1mm with stepwise grid point intervals. The probe was inclined to the airfoil surface so as to minimize the blockage effects caused by the probe prong as well as probe support. The probe positioning especially to the starting point was carefully made using the long-established traverse system originally developed by Tanaka [14], whose reliability was checked through the several sets of cascade tests, including the numerical data obtained by LES (Large-Eddy Simulation) analysis [4]. Note that the measurement on the pressure surface was made only at a single location close to the airfoil trailing edge as shown in Figure 4 due to the difficulty in probe insertion.

Test airfoils and loading index
This study dealt with six different LPT airfoils with different pitches, pressure distributions and loading indices. Figure 5 shows rough images of the tested airfoils, along with the values of design inlet and outlet angle. They are called Design A-F. Since all test airfoils were designed under the same design concept, their turning angles did not differ so much, ranging from 104.4 [deg] to 108.2 [deg], while the solidity varies among the airfoils. Table 1 describes the characteristics of each of the test airfoils, containing two important indices related to aerodynamic loading of each airfoil, DR and Zw. The trailing edge diameter was 2.7%Cx for all test airfoils.

DR, defined by Eq. (2), is an index representing a non-dimensional flow deceleration rate over the suction surface,

\[ DR = \left( \frac{U_{max} - U_{tr}}{S_{U_{max}} - S_{U_{tr}}} \right) / S_{tr}, \]  

(2)

where \( U_{max} \) and \( U_{tr} \) are the velocities at the suction peak position and at the location near the trailing edge shown in Figure 4 with TE, which were calculated from the measured static pressure distributions around the airfoils. As will be shown later, the value of DR for one type of the test airfoil varies with the Reynolds number because \( U_{max} \) depends on the flow condition. The values of DR in Table 1, which are normalized by a reference value DRref, are for Re=100,000.

Zw is the Zweifel loading factor proposed by Zweifel [14], which implies a non-dimensionalized tangential force exerted on the airfoil. It can be defined for the incompressible flow by

\[ Zw = \frac{2 \cos^2 \beta_0}{\sigma} (\tan \beta_1 - \tan \beta_2). \]  

(3)

It is commonly accepted that the airfoil Zw >1 can be regarded as a highly-loaded one.

Apart from those two indices, the load peak position was determined from the static pressure distribution given by

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

(4)

Table 1 Test airfoils with their characteristics

<table>
<thead>
<tr>
<th>Airfoil</th>
<th>Zw [-]</th>
<th>DR/DRref</th>
<th>Load peak [% Cx]</th>
<th>Max val. of Cp [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design A</td>
<td>1.09</td>
<td>0.58</td>
<td>47</td>
<td>1.51, 1.56, 1.58</td>
</tr>
<tr>
<td>Design B</td>
<td>1.09</td>
<td>0.78</td>
<td>60</td>
<td>1.51, 1.56, 1.60</td>
</tr>
<tr>
<td>Design C</td>
<td>1.15</td>
<td>0.78</td>
<td>49</td>
<td>1.61, 1.67, 1.68</td>
</tr>
<tr>
<td>Design D</td>
<td>1.25</td>
<td>1.05</td>
<td>50</td>
<td>1.76, 1.81, 1.79</td>
</tr>
<tr>
<td>Design E</td>
<td>1.26</td>
<td>1.72</td>
<td>63</td>
<td>2.02, 2.00, 2.06</td>
</tr>
<tr>
<td>Design F</td>
<td>0.98</td>
<td>0.35</td>
<td>66</td>
<td>N/A, 1.31, N/A</td>
</tr>
</tbody>
</table>

All DR values were obtained at Re=100,000

According to the above-mentioned airfoil aerodynamic characteristics, Zweifel factor, and the loading distribution, all
tested airfoils can be mapped as shown in Figure 6. Design A is a baseline, typical front-loaded high-lift airfoil with Zw = 1.09 and DR/DRref = 0.58. Design B is an aft-loaded airfoil with almost the same loading level as Design A, while its DR is larger than that of Design A. Design C and Design D are slightly aft-loaded airfoils by expanding the airfoil pitch so that their higher Zweifel factors become larger than that of Design A (Zw = 1.15 and Zw = 1.25). Design E is also an aft-loaded airfoil with large pitch, resulting in the Cp peak position at 63% Cx. Since the solidity of Design E is very low, its Zweifel factor and DR are the highest of all the test cases (Zw = 1.26, DR/DRref=1.72). In contrast to Design A – E, Design F is a moderately loaded airfoil with Zweifel factor less than unity and DR less than that of Design A.

Test conditions
The tested Reynolds numbers, defined by
\[ Re = \frac{U_C}{\nu} \] (5)
were 57,000, 100,000 and 170,000. The Strouhal number ranged from 0.4 to 1.2, by changing the bar speed and/or bar pitch (bar count). It should be noted that the bar speed could not be increased so as to attain St>0.8 at Re=100,000 and St>0.4 at Re=170,000 due to the mechanical restriction. As mentioned above, the FSTI in this study was about 1.2% (low FSTI) and 3.5% (high FSTI). Inlet Mach numbers were less than 0.05 for all test conditions. Inlet flow angle was set almost to the design angle for each airfoil, which was confirmed through the static pressure measurement.

Stagnation pressure loss and cascade loss
Stagnation pressure loss coefficient Yp is defined by
\[ Y_p(y) = \frac{p_{out}(y) - p_{in}(y)}{1/2 \rho U_C^2} \] (6)
where the inlet stagnation pressure p_{in} was measured downstream of the wake-generating bars. Integration of this coefficient over one pitch yields the mass-averaged cascade loss coefficient by using the following equation, assuming constant outlet flow angle,
\[ \zeta_u = \int_{-0.5}^{0.5} Y_p(y/c)U_{c,2}(y/c)dy/c \int_{-0.5}^{0.5} U_{c,2}(y/c)dy/c \] (7)

Loss estimation based on Denton’s approach
Denton [9] proposed the expression to predict the cascade loss, based on the momentum theory along with several assumptions, one of which was that the static pressure over the uncovered suction surface (p_u) equals the cascade outlet pressure (p_c). However, as will be shown in the static pressure distributions, this assumption did not hold especially for high-lift airfoils due to the flow deceleration. Several derivatives of the original Denton’s theory were proposed, for example, by Cadrecha, Vazquez [16] and Zhou et al. [17]. According to their new expressions, the present study employed the following expression as Denton-type cascade loss coefficient, mainly to grasp an estimation of cascade loss, which will be compared with the mass-averaged cascade loss coefficient given by Eq. (7),
\[ \zeta_D = \frac{\bar{p}_d - \bar{p}_o}{1/2 \rho U_C^2} \] (8)
\[ = (-\frac{Ct_{TE}}{w}) + (\frac{2\theta_{TE,SS} + 2\theta_{TE,PS}}{w}) + (\frac{\delta_{TE,SS} + \delta_{TE,PS} + \delta_{TE}}{w})^2 \] (8)

Displacement and momentum thicknesses were calculated by
\[ \delta = \int_{0}^{\infty} (1 - \frac{u(y/c)}{u(y/c)_b})dy/c \] , \[ \theta = \int_{0}^{\infty} \frac{u(y/c)}{u(y/c)_b}dy/c - 1 \] (9)

Base pressure coefficient C_{pb} is defined by Eq. (10),
\[ C_{pb} = \frac{p_{base} - \bar{p}_o}{1/2 \rho U_C^2} \] (10)
where p_{base} is a base pressure.
To calculate the loss coefficient from Eq. (8), displacement/momentum thicknesses of the boundary-layer on the suction and pressure surfaces near the trailing edge, and base pressure coefficient C_{pb} are required. While the boundary-layer thicknesses were directly obtained from the hot-wire probe measurements applying trapezoidal rule to Eq. (9), it was difficult to determine the base pressure coefficient experimentally. Likewise in the previous study [13], this study employed RANS simulation using ANSYS CFX (ANSYS) to calculate the base pressure coefficient, where the detailed explanation on the calculation process is skipped here.

Figure 7 demonstrates an example of RANS simulations, indicating static pressure distributions around the trailing edge of the airfoil Design A for low FSTI at Re=100,000 with no incoming wakes. As shown in this figure, the present study used the pressure obtained at the TE center as p_{base}. Note that this definition was based on that of Zhou et al. [17] in which the base pressure was directly measured using a pressure hole placed on the trailing edge, while Denton’s method employed averaged constant base pressure. Interestingly, Zhou et al. made a direct comparison between RANS-based and measured C_{pb}, finding that their RANS simulations with transition model successfully provided a reasonable agreement with the measured data. Despite those observations, since the base region is usually characterized by very complex flow phenomena with intense unsteadiness, some errors associated with the steady-state simulation cannot be avoided in the estimation of base pressure loss. However, the errors can be considered to be a limited impact to the total loss estimation due to the dominating contribution of the second term in Eq. (8), as found in [13].
Uncertainty

Uncertainty associated with the pneumatic measurement was governed by the accuracy of pressure transducers. Since the accuracy of the pressure transducer was ±0.5 Pa for the lowest Reynolds number, the standard procedure [18] determined that uncertainty of the inlet velocity \( U_1 \) was about ±1.7% and static pressure coefficient uncertainty was ±3.5% around the peak region of the coefficient. The uncertainty of the loss coefficient defined by Eq. (6) was about ±7% at the center of the wake. The accuracy of the hot-wire probe measurement was mainly dominated by the probe calibration process using a Pitot tube to determine the reference velocity and the uncertainty of the hot-wire probe measurement away from the wall was estimated to be about ±2%, while the measurement in the wall vicinity tended to have larger uncertainty (more than 5% in magnitude) due to the decrease in streamwise velocity, wall cooling effect, etc. The uncertainties of displacement and momentum thicknesses calculated by Eq. (9) were about ±2.5% and ±4.0%, respectively.

MEASUREMENTS WITH NO BAR WAKES

Static pressure measurements

Figure 8 exhibits static pressure distributions for four high-lift test airfoils at three Reynolds numbers under the high FSTI condition without incoming bar wakes, where St00 means no wake condition and R57, R10, R17 stand for Reynolds numbers of 57,000, 100,000 and 170,000, respectively. Figure 8(a) contains an explanatory figure to show the relationship between change in curvature of the pressure distribution and boundary layer separation and its reattachment.

As mentioned in the above, Design A is a front-loaded high-lift airfoil whose pressure distribution exhibits the existence of small separation bubble at Re=57,000 and 100,000, while Design B is an aft-loaded airfoil with its DR larger than that of Design A, leading to the clear appearance of separation bubble on the suction surface at Re=170,000 even under the high FSTI condition. As for Design D and E, due to their high level of the airfoil loading, each of the static pressure distributions indicates the existence of large-scale separation bubble, resulting in large cascade loss, as will be described later. Design E is also an aft-loaded with the \( C_p \) peak position at 63%\( C_x \). Since the solidity of Design E is very low, its Zweifel factor and DR are the highest of the all test cases, as shown in Table 1. Accordingly, its static pressure distribution indicates a distinctive feature of the occurrence of very large separation bubble.

Since DR is defined as a velocity change along the airfoil suction surface, it may be more useful to re-plot each of the static pressure distributions on the suction surface against the corresponding non-dimensional suction surface length for quantitative understanding of DR, change in streamwise extent of separation bubble. Those plots are shown in Figure 9(a)-(c) for three Reynolds numbers, respectively.
Figure 9 Suction surface static pressure distributions against the non-dimensional surface length for four different types of high-lift airfoils with no incoming wakes (a) Re=57,000 (b) Re=100,000 (c) Re=170,000

Boundary-layer measurements
Figure 10 demonstrates velocity (left) and RMS (Root-Mean Squared value) (right) contours obtained from the boundary-layer measurements of Design A at Re = 100,000 under the low and high FSTI conditions. Note that these contours are depicted in the Cartesian coordinate system with the horizontal and vertical axes being the surface length and the distance from the surface. As already confirmed from the static pressure measurements shown in Figure 8, there existed a separation bubble over the suction surface at least at Re=100,000. In comparison with the low FSTI case, in which a long separation bubble appearing on the suction surface was accompanied by rather an abrupt transition so as to become turbulent near its rear part, the separation bubbles in the high FSTI case experienced instability growing along its shear layer, resulting in earlier reattachment.

Cascade loss measurements
Figure 11 shows stagnation pressure loss coefficient profiles measured downstream of the test airfoils for the three Reynolds number cases. Note that all loss values shown in this study were normalized by the reference loss coefficient, that is, mass-averaged loss coefficient of Design A at Re=100,000 with no wake under the low FSTI condition.

It is evident from Figure 11(a) that a considerable amount of loss was generated on the suction surface of Design E due to the appearance of huge separation bubble. The three other loss profiles were similar in shape, while the peak loss value and relative profile width of Design D was the largest among the three cases. As the Reynolds number increased, the contribution of separation bubble on Design E suction surface tended to decrease and the all loss profiles became almost the same at Re=170,000. This implies that their mass-averaged loss coefficients were on a similar level at this Reynolds number condition. It can be also mentioned that the pressure side loss profiles for the high FSTI did not exhibit any drastic change with the Reynolds number, while those for the low FSTI visibly varied with the Reynolds number [13].
stagnation pressure loss profiles measured downstream of the test airfoils for no incoming wake condition under the high FSTI condition (a) Re=57,000 (b) Re=100,000 (c) Re=170,000

Figure 12 demonstrates the relationship between mass-averaged cascade loss coefficients and DR obtained at the three Reynolds numbers under the high FSTI condition, along with the results for the low FSTI in order to clarify effects of FSTI on the cascade loss. Again, the loss coefficients were normalized by that of Design A at Re=100,000 under the low FSTI condition. The loss coefficients at Re=57,000 and 100,000 considerably increased with DR, where the higher FSTI suppressed their growing rates to a great extent. In fact, at Re=57,000 the averaged cascade loss increased by more than a factor of 2 from Design A to Design E for low FSTI condition, while the loss increase was about 60% for high FSTI. Nevertheless, the cascade loss correlated closely with DR. In contrast, the loss coefficients at Re=170,000 did not show any clear dependency on DR and effects of FSTI on the loss reduction remained very limited, with the increase rate less than 20%. This tendency of Re=170,000 case was consistent with the result observed in Figure 11(c).

From those findings, along with the fact from the previous study [13] that for the low FSTI cases there existed a strong correlation between DR and the suction surface momentum thickness near the trailing edge, one of the main contributors in Eq. (8), DR defined by Eq. (2) could be a proper index to judge the loading level of; eventually steady-state loss level of, an airfoil developed on the basis of a similar design concept of the tested airfoils in this study, at least up to Re=100,000.

Figure 12 Mass-averaged loss coefficients for no incoming wake condition

MEASUREMENTS WITH BAR WAKES

Static pressure measurements
Figure 13 demonstrates static pressure distributions for five high-lift airfoils at three Reynolds numbers under the low FSTI condition with incoming bar wakes, where St was 0.8 except for Re=170,000 because of mechanical restriction. Note that the data of Design F are available only for Re=100,000. Comparisons between Figures 8 and 12 have revealed that the wake passing was able to suppress the separation bubble more effectively than FSTI in this study so that the extent of pressure plateau for Design E or the level of pressure recovery from transition to reattachment (see Figure 8(a)) for Design D was considerably reduced. A similar discussion will be made in the following.

Boundary-layer measurements
As seen in the pressure distributions, the bar wake passing was effective in suppression of the separation bubble, which was also confirmed by the boundary-layer measurements. Figure 14 shows the time-averaged velocity and RMS contours obtained on the suction surface of Design D for St=0.0 (no wake), 0.4,0.8 and 1.2 at Re=57,000. It follows from these contours that the separation bubble tended to be suppressed as the Strouhal number increased, so that the height and streamwise extent of the separation bubble was gradually decreased. Accordingly, the
maximum value and the high-value area of RMS contours were also reduced, implying a possibility that the contribution of separated boundary layer to the cascade loss could be lessened by the wake passing. However, such a favorable impact of the wake passing tended to saturate as St increased, which can be confirmed by comparing two velocity or RMS contours for St=0.8 and 1.2. Moreover, since the bar wakes can be an additional contributor to the cascade loss through their deformation and mixing processes in the blade-to-blade passages, the bar wakes may not be always beneficial to the total cascade loss reduction, as will be discussed later.

Figure 13 Static pressure distributions for five different types of high-lift airfoils with incoming wakes (a) Re=57,000 (b) Re=100,000 (c) Re=170,000

Figure 14 Velocity and RMS contours measured over the suction side of Design D for several Strouhal numbers at Re=57,000

Cascade loss measurements

The normalized stagnation pressure loss profiles are shown in Figure 15 for the three Reynolds number conditions. As mentioned in the above, the bar wake passing was effective in suppression of the separation bubble. On the other hand, it is obvious from Figure 15 that the bar wakes caused some additional loss in the blade-to-blade passage, while the profile losses originating from the airfoils themselves did not change in shape from those obtained under no wake/high FSTI conditions, except for the cases of Design E. It can be also mentioned that the loss peak positions were different with each other, which was in contrast to the finding in Figure 11.

Figure 16 shows the relationship between mass-averaged cascade loss coefficients and DR obtained at the three Reynolds numbers under incoming wakes and low FSTI conditions for several Strouhal numbers, including the data for St=0.0 duplicated from Figure 12. Since all loss coefficients are normalized with the same reference value, a direct comparison between the data in Figures 12 and 16 is possible.
Several important findings from this comparison are as follows. It is found that the overall cascade loss levels were enhanced in comparison with those obtained under the no wake conditions except for the highest DR at Re=57,000 and 100,000. In addition, the loss levels increased with the Strouhal number, irrespective of the Reynolds number. It can be conjectured from the findings in Figure 15 and the discussion which will be made later that the loss increase due to the wake passing was caused by mainly bar wakes themselves through their deformation and mixing processes. On the other hand, the DR dependency of the wake-affected loss coefficients became rather complicated than those for no wake condition exhibiting monotonous increase with DR. In fact, at Re=57,000, when DR/DR_ref was around or less than unity, the wake-affected loss coefficients varied faintly with DR for St=0.4 and 0.8 and there appeared a minimum point for St=1.2. The loss coefficients measured at Re=100,000 exhibited only slight variation with DR, having a less pronounced minimum value for St=0.4 around DR=1. Furthermore, a minimum value was also found in the wake-affected loss coefficients measured at 170,000 for St=0.4. It should be stated that the abovementioned minimum values tended to appear at larger DR as the Reynolds number increased.
Figure 17 is to examine effects of FSTI on the wake-affected cascade loss coefficients. It is clear that FSTI did not drastically change the values of wake-affected cascade loss coefficient and overall tendency seen in Figure 16 remained almost unchanged. This means that the incoming bar wakes hold a dominant impact on the cascade loss in comparison with that of FSTI.

DISCUSSIONS

The minimums of wake-affected cascade loss

Although the reason for the appearance of the minimum wake-affected loss against DR, especially at Re=57,000 for St=1.2 and at Re=170,000 in Figure 16 or 17 is not clear, it can be mentioned that unfavorable effects of incoming wake on the cascade loss, such as loss directly associated with the structure of bar wakes might have been altered while the wakes passed through different types of blade-to-blade passages. In fact, using high quality LES on the flow field around the cascade called T106A, Michelassi et al. [19] found that the incoming wakes had a strong effect on the loss generation. Furthermore, Mitsukawa et al. [20] have found from their CFD (Unsteady RANS) and experimental studies on two different airfoils that the loading or static pressure distributions considerably influenced mixing process of bar wakes in the passage.

Further studies are strongly needed to examine the mechanism of the above-mentioned behavior of the loss. In addition, it is desired to confirm whether the minimum loss could occur for different flow conditions. For this purpose, a new wind tunnel with a more sophisticated wake-generator is now under construction.

Loss estimation by Denton-type method

Figure 18 shows the comparison between the measured cascade loss with and without incoming wakes and the predictions obtained by Denton-type estimation method (Eq. (8)) or “control-volume loss” according to Michelassi et al. [19]. Each data point in this figure is plotted based on the pneumatic probe measurement (vertical direction) and on the Denton-type estimation method using the results of the boundary-layer measurement as well as RANS simulation (horizontal direction). The mass-averaged loss coefficients are normalized by the reference mass-averaged loss coefficient and the estimations are normalized by the corresponding reference value.

In the figure, the data at three Reynolds numbers under the unsteady conditions are plotted. If the loss values by the two methods coincide with each other, the plotted points are on the solid straight line, otherwise the predictions is underestimated or overestimated and the plotted point deviates from the solid line accordingly. Looking at Figure 18, it is found that the predicted loss values for St=0.0 represented by solid symbols (no wakes) are almost within about ± 10 [%] at all Reynolds numbers, and almost all the plots are located near the solid line. It seems from this comparison that the Denton-type estimation method was able to predict the steady-state mass-averaged cascade loss to a reasonable level.

In contrast, it was not the case for the unsteady flow conditions. In fact, most of the unsteady data (open symbols) are located upper side of the solid line and many of them appear outside of ± 10 [%] area, implying that Eq. (8) failed to make a reasonable prediction of the mass-averaged cascade loss measured under the incoming wake conditions. However, this discrepancy cannot be helped because the Denton’s theory does not take the existence of incoming wakes into account. Indeed, Michelassi et al. [19] found from their numerical simulations on T106 airfoils that the difference between their unsteady loss evaluations and the control-volume loss reached about 15%, which was attributed mainly to wake distortion effects, depending on the reduced frequency defined by an expression similar to Eq. (1).

CONCLUSIONS

This study executed experimental investigations, with the aid of RANS calculations, on aerodynamic loss of 6 types of LP turbine airfoils with different velocity deceleration rates (DR) on their suction surfaces, focusing on the effects of incoming wakes and freestream turbulence. Furthermore, the obtained cascade loss coefficients were compared with those predicted by the Denton-type estimation method. The following findings were obtained through this study.

1. Measurements without incoming wakes
   • Under the low FSTI condition (about 1.2%) without incoming wakes, the cascade loss coefficients
increased monotonously with DR at Re=57,000 and Re=100,000, while the loss increase with DR was quite moderate at Re=170,000. When the FSTI was elevated up to 3.5%, the loss increase rates were drastically reduced at Re=57,000 and Re=100,000. However, at Re=170,000 the elevated FSTI barely affected the loss coefficients.

- From the present findings, along with those from the previous study [13], DR defined by Eq. (2) could be a proper index to judge the loading level of, eventually steady-state loss level of an airfoil developed on a design concept similar to that of the tested airfoils in this study, at least up to Re=100,000.

2. Measurements with incoming wakes

- The measurements on the static pressure distribution, boundary layer and loss profile revealed that the upstream wake passing was effective in suppression of the separation bubble, whereas the wakes were accompanied with some additional loss in the blade-to-blade passage, leading to the increase in cascade loss coefficient with the Strouhal number.

- DR dependency of the wake-affected cascade loss coefficients became rather complicated than those for no wake condition, implying that DR was not a determining parameter of the cascade loss under the influence of incoming wakes. Minimum values were found in the loss coefficients in spite of the fact that the additional loss was generated by the bar wakes passing through the cascade. These phenomena seem to be linked to the bar wake structure experiencing some alternation such as distortion, mixing while the wakes passed through the blade-to-blade passage, although the reason of the appearance of the minimums remains unclear.

3. Validity of the Denton-type estimation method

- By the direct comparisons between the measured cascade loss coefficients and the predictions using Denton-type estimation method, it was found the measured values for no wake condition fell mostly within +/-10% range from the predictions.

- Denton-type estimation method failed to make a reasonable prediction of the cascade loss measured under the incoming wake conditions. It was because the Denton’s theory does not take the existence of incoming wakes into account, whereas the wakes have some impact on the cascade loss via the effects of wake distortion, mixing and so on.

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REFERENCES


