Detailed Studies on Separated Boundary Layers over Low-Pressure Turbine Airfoils under Several High Lift Conditions: Effect of Freesteam Turbulence

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ABSTRACT
This paper deals with experimental investigation on the interaction between inlet freestream turbulence and boundary layers with separation bubble on a low-pressure turbine airfoil under several High Lift conditions. Solidity of the cascade can be reduced by increasing the airfoil pitch by 25%, while maintaining the throat in the blade-to-blade passage. Reynolds number examined is 57000, based on chord length and averaged exit velocity. Freestream turbulence intensity at the inlet is varied from 0.80% (no grid condition) to 2.1% by use of turbulence grid. Hot-wire probe measurements of the boundary layer on the suction surface for Low Pressure (LP) turbines rotor are carried out to obtain time-averaged and time-resolved characteristics of the boundary layers under the influence of the freestream turbulence. Frequency analysis extracts some important features of the unsteady behaviors of the boundary layer, including vortex formation and shedding. Numerical analysis based on high resolution Large Eddy Simulation is also executed to enhance the understanding on the flow field around the highly loaded turbine airfoils. Standard Smagorinsky model is employed as subgrid scale model. Emphasis of the simulation is placed on the relationship of inherent instability of the shear layer of the separation bubble and the freestream turbulence.

Nomenclature
- \( C \) : blade chord length
- \( C_{ax} \) : blade axial chord length
- \( C_{y} \) : static pressure coefficient
- \( E(k) \) : turbulent energy spectrum
- \( f_{K-H} \) : frequency of K-H instability wave
- \( H_{12} \) : shape factor
- \( h \) : thickness of shear layer
- \( K \) : total turbulence kinetic energy
- \( k_n \) : wave number vector for \( n \)-th mode \( (= (k_1, k_2, k_3) ) \)
- \( k' \) : unit vector normal to \( k \) \( (= (k'_1, k'_2, k'_3) ) \)
- \( k_x \) : wave number, Kolmogorov wave number
- \( L \) : turbulence length scale
- \( N \) : number of modes
- \( N_d, N_r \) : data size, number of realizations
- \( P_{in}, P_{ex} \) : inlet and outlet stagnation pressure
- \( \rho(x) \) : static pressure on the airfoil surface
- \( Re_{ch} \) : Reynolds numbers based on chord length and exit averaged velocity
- \( Tu_{in} \) : inlet turbulence intensity
- \( \theta, \Delta t \) : airfoil pitch, sampling time interval

\( U_{in, \bar{U}} \) : inlet and exit averaged velocities
\( U_{ref} \) : reference velocity (edge velocity)
\( u, \bar{u} \) : instantaneous and ensemble-averaged velocities
\( x, y, z \) : axial direction, surface length
\( Y_s \) : stagnation pressure loss coefficient
\( y, y_x, y_z \) : tangential direction, normal direction to the surface
\( \delta, \delta_x, \delta_z \) : displacement and momentum thickness using time-averaged velocity
\( \lambda \) : wave length
\( \sigma \) : solidity (= \( C/t \) )
\( \Delta k^* \) : viscous wall unit based on streamwise grid spacing
\( \Delta p^* \) : viscous wall unit based on heightwise grid spacing
\( \Delta C^* \) : viscous wall unit based on spanwise grid spacing

Superscript
- \( f, \bar{f} \) : ensemble-averaged and time-averaged values of \( f \)

Subscript
- \( base \) : base condition
- \( in, 2 \) : inlet, outlet

Abbreviation
- FST : Freestream Turbulence
- HL : High Lift
- RRS : Reduction Rate of Solidity
- SNGR : Stochastic Noise Generation and Radiation
- UHL : Ultra-High Lift

1. INTRODUCTION
Great efforts have been devoted experimentally and numerically to the development of high lift (HL) or ultra high lift (UHL) low-pressure (LP) turbine blades for civil aeroengines during the last decade, with the motivation to realize drastic reduction of the blade count and engine weight. One big problem associated with the development of UHL LP turbine blade is no doubt the increase in profile loss due to flow separation on the blade suction surface, particularly at cruise condition where Reynolds number of the flow field around the turbine becomes smaller and most of the boundary layer on the blade surface could be anticipated to remain laminar if no disturbances existed in the flow field. In reality, however, in the flow field there are some factors that seriously affect the separation bubble such as wake interaction or free-stream turbulence. As for the wake interaction, a number of relevant studies have been made over the last two decades (for example, [1] – [4]), and it is nowadays recognized that the LP turbine blade design space, which was once restricted due to the appearance of loss-inducing separation or separation bubble, is
now being expanded by incorporating the effects of stator wake interaction with rotor blade into the blade aerodynamic design process. Effects of freestream turbulence (FST) upon the separation bubble have also been investigated by many researchers. For example, Shyne et al. [5], Volino and Hultgren [6], Volino [7, 8], Zhang and Hodson [9] conducted detailed measurements of separated boundary layers influenced by freestream turbulence with various turbulence intensities using flat-plate or cascade. In contrast to those experimental approaches, there are fewer numerical studies that dealt with the freestream effects on the separation bubble. Suzen et al. [10] conducted RANS (Reynolds-Averaged Navier-Stokes equations) - based investigations to see the impact of elevated freestream turbulence on the transitional characteristics of boundary layers including separation bubble. Suzen et al. [11] also conducted comprehensive studies on transitional flows in LPT using P&W Pak-B airfoil under several Reynolds numbers and inlet freestream turbulence intensities.

Recently, the present authors made an LES (Large-Eddy Simulation)-based numerical investigation on the flow field around UHL and HL LPT cascades, focusing on the effects of FST [12]. Stochastic Noise Generation and Radiation (SNGR) method using von Karman-Pao turbulent energy spectrum was employed there in order to create inlet turbulent flow field as inlet boundary condition. Although the LES-based investigation successfully revealed the critical role of elevated FST in the transition of the separation bubble, including roll-up process of the shear layer and its spanwise distortion, it was also confirmed that further refinement of the numerical approach along with elaborate experiments was needed to deepen the understanding of the importance of incident freestream turbulence on the transitional behavior of separated boundary layer approach.

This paper is the follow-up study of the previous work [12], dealing with the investigations on the flow field around an LP turbine cascade of high-lift and ultra-high-lift conditions under the influence of freestream turbulence, aiming at the clarification on how the inlet freestream turbulence affects the transitional behavior of the boundary layer on the blade suction surface before and after the separation. The focus of this study is especially on the relationship between K-H (Kelvin-Helmholtz) instability of the shear layer of the separation bubble and the freestream turbulence under several flow conditions. Detailed boundary layer measurements using a single hot-wire probe along with the results from their frequency analyses provide experimental evidence showing the impact of inlet FST on attached as well as separated boundary layer. Time-accurate LES analysis is also carried out using the artificial inlet turbulence likewise in the previous study [11] with some modifications. The LES analysis provides clear three-dimensional and unsteady images of the transition of the separated boundary layer.

2. Experimental Setup

2.1 Test Section and Cascade

Since the test apparatus used was the same as that used in the previous study done by Funazaki et al. [12], only a brief description of it is given in the following. Figure 1 shows the test apparatus including the test linear cascade and turbulence grid. Note that the belt appearing in this figure in this apparatus was not used. The linear cascade consisted of seven airfoils whose geometrical information on the airfoil and cascade is listed in Table 1. The cross-section of the cascade airfoil is a typical one for modern commercial aeroengines and its Zweifel factor is almost the same as that of the airfoil employed by Hoheisel et al.[13], where their Zweifel factor was around 1.05. Pitchwise periodicity of the cascade was established through the adjustment of the two side plates shown in Figure 1 repeated until satisfactory periodicity of the cascade exit flow field was achieved so that the difference between the stagnation pressures measured at the both ends fell within less than 1 Pa. Two instrumented brass airfoils were in the middle of the cascade to measure static pressure distributions around the blade surface. Each of the airfoils, which are designated Blade #3 and Blade #4 in Figure 2, had 30 pressure holes of 0.5 mm diameter on its suction or pressure surface. The pitch of the cascade was changeable by inserting plates into the in-between spaces of the neighboring airfoils. Blade #4 was the target airfoil on which boundary layer measurements were made.

Figure 1 The test apparatus, showing LPT cascade, turbulence grid and contraction nozzle (unit in mm)
Table 1  Airfoil geometry and cascade configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chord length $C$</td>
<td>114mm</td>
</tr>
<tr>
<td>Axial chord length $C_a$</td>
<td>100mm</td>
</tr>
<tr>
<td>Span</td>
<td>260mm</td>
</tr>
<tr>
<td>Pitch $t$</td>
<td>60deg</td>
</tr>
<tr>
<td>Inlet flow angle $\beta_1$</td>
<td>47deg</td>
</tr>
<tr>
<td>Outlet flow angle $\beta_2$</td>
<td>-60deg</td>
</tr>
</tbody>
</table>

Table 2  Turbulence grids used in this study

<table>
<thead>
<tr>
<th>Grid</th>
<th>Mesh size</th>
<th>Wire diameter</th>
<th>Turbulence level</th>
<th>Integral length scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>TG04</td>
<td>4 mm</td>
<td>0.2 mm</td>
<td>1.1%</td>
<td>3.8 mm</td>
</tr>
<tr>
<td>TG16</td>
<td>16 mm</td>
<td>2 mm</td>
<td>2.0%</td>
<td>8.4 mm</td>
</tr>
<tr>
<td>No grid</td>
<td></td>
<td></td>
<td>0.8%</td>
<td></td>
</tr>
</tbody>
</table>

Two types of turbulence grids were employed in this study to change the inlet FST, as shown in Table 2 along with the data for no grid condition. The grid was placed 766 mm upstream of the center airfoil in the cascade, as shown in Figure 1. Although the turbulence grid was not parallel to the cascade due to the mechanical constraint of the test apparatus, it was found that the resulting pitchwise non-uniformity of the flow properties such as turbulence intensity was insignificant at least over the inlet plane covering three middle airfoils in the cascade. Figure 3 depicts some examples of the inlet turbulence data measured for the three cases shown in the above. In fact, the turbulent flow field created by TG16 does not seem to be fully random, implying that it is not easy to correctly model this type of turbulent flow characteristics only by means of creating pseudo-isotropic turbulence.

2.2 Instruments and Data Processing

As mentioned above, two instrumented airfoils were in the middle of the cascade. Static pressure coefficient was defined as

$$C_p(x) = \left( P_{in} - p(x) \right) \frac{1}{\frac{1}{2} \rho U_e^2} ,$$

where $P_{in}$ is inlet stagnation pressure and $U_e$ is the averaged exit velocity.

Aerodynamic loss profiles at midspan were obtained by measuring inlet and outlet total pressures by use of two miniature Pitot tubes (F202 Standard JIS Type, Tsukuba Rika Seiki) at 15% $C_a$ downstream of the trailing edge of the target airfoil along the axial direction. The radius of the probe sensing head was 1.5mm and the radius of the stagnation pressure hole was 0.75mm.

The probe located downstream of the cascade was aligned with the exit flow direction from the cascade, using a tuft as flow indicator. This alignment was afterward validated by the measurement using a three-hole hotwire or by CFD. A PC-controlled traversing device positioned the downstream Pitot tube over the two-pitch exit flow region along the measurement plane. Stagnation pressure loss coefficient $Y_p$ was then calculated by the following definition,

$$Y_p(y) = \frac{P_{in} - P_{out}(y)}{\frac{1}{2} \rho U_e^2} ,$$

where $P_{in}$ was the outlet stagnation pressure distribution.

As shown in Figure 2, the hot-wire measurement zone extended over the blade suction surface from $x/C_a = 0.5$ to the airfoil trailing edge in the streamwise direction and from $y_0 = 0.2 \text{mm}$ to $10 \text{mm}$ in the direction normal to the blade surface. The probe positioning machine, which was installed by the side of cascade, enabled the hot-wire probe to be automatically placed very close to the suction surface along the normal lines to the surface. A single hot-wire probe (Dantec 55P11) connected to Kanomax CTA (Constant Temperature Anemometer) unit produced instantaneous velocity data, which were then A/D converted and stored in the PC with sampling frequency of 20 kHz. The size of each of the realizations, $N$, was $2^{13}$ word. Ensemble-averaged velocity $\bar{u}$ was calculated from these 1 velocity data, $u_i (k=1, \ldots, N_j)$ as follows,

$$\bar{u}(x, y, j \Delta t) = \frac{1}{N_j} \sum_{j=1}^{N_j} u_i (x, y, j \Delta t) , \quad j = 0, \ldots, N_d - 1 , \quad (3)$$

where $\Delta t$ was data sampling interval ($= 50 \mu s$), $N_d$ was the number of the realizations used for ensemble averaging ($= 100$).

The time-averaged velocity $\overline{\bar{u}}(x, y)$ was calculated from the arithmetic average of $\bar{u}$. One may wonder why the ensemble averaging was necessary here. It was because the program used for the data process was originally prepared for the experiment using the wake generator to create periodic disturbances. In the present case ensemble-averaged data were actually equivalent to time-averaged data.

Ensemble-averaged boundary layer integral parameters, i.e., displacement and momentum thicknesses $\delta_1$, $\delta_2$, and shape factor $H_{12}$ were calculated as follows.

$$\delta_1(x, j \Delta t) = \frac{\int_0^{x} 1 - \bar{U}_e(U_e - \bar{U}_e) dU_e}{\int_0^{x} 1 - \bar{U}_e(U_e - \bar{U}_e) dU_e} , \quad (4)$$

$$\delta_2(x, j \Delta t) = \frac{\int_0^{x} \bar{u}(x, j \Delta t) \left(1 - \frac{\bar{U}_e(U_e - \bar{U}_e)}{U_e} \right) dU_e}{\int_0^{x} \bar{u}(x, j \Delta t) \left(1 - \frac{\bar{U}_e(U_e - \bar{U}_e)}{U_e} \right) dU_e} , \quad (5)$$

$$H_{12}(x, j \Delta t) = \frac{\delta_1(x, j \Delta t)}{\delta_2(x, j \Delta t)} , \quad (6)$$

where the boundary layer thickness $\delta(x, j \Delta t)$ was defined as the height at which the streamwise velocity reached 98% of the maximum velocity $U_e$, attained within the measurement range. To calculate the time-averaged values of the above-mentioned integral parameters, the time-averaged velocity was used instead of the ensemble-averaged one in Eqs. (4)-(6).

In consideration of the low flow speed in the experiment, where the inlet velocity was about 5m/s and the outlet velocity was about 9m/s, a highly precise transducer (DMP-301N1, Okano...
Works, Ltd) with less than ±0.5 Pa reading error was used to measure inlet, outlet velocities and stagnation pressures. Since the miniature Pitot was expected to be insensitive to flow angle within ±10°, it was then found that the uncertainties of the inlet velocity \(U_i\) and static pressure/stagnation pressure loss coefficients were about ±1.7% and ±3.5%, respectively. Besides, the uncertainty of the hot-wire probe measurement, which was mainly due to the calibration error, was estimated at about ±2%.

### 2.3 Test Conditions

This study examined the flow fields for two solidity cases with the exit Reynolds number fixed at \(Re_z = 5.7 \times 10^6\), where the Reynolds number was defined as follows,

\[
Re_z = \frac{C_U z}{v}.
\]  

The solidity of the cascade examined was expressed in terms of relative reduction rate of the solidity from the original. The solidity reduction rates \(RRS\) was defined as

\[
RRS = 1 - \frac{\sigma}{\sigma_{base}}.
\]  

The test case of \(RRS = 14.2\%\) is designated S-15 hereafter and sometimes referred to as HL condition. The other test cases were for \(RRS = 18.9\%\) and \(23.6\%\) and will be called S-20 and S-25 or UHL1 and UHL2 conditions, respectively. The corresponding Zweifel factor became 1.14 and 1.23 times of the base airfoil for HL condition and UHL2 conditions, respectively.

Figure 4 shows a comparison of the static pressure distributions among the three RRS cases with no grid condition. The reduction of solidity augmented the blade aerodynamic loading, while shorter separation bubble and abrupt pressure recovery occurred for higher loading case. Note that the dependency of the separation bubble length on the aerodynamic loading will be revisited in the discussions of boundary layer measurement shown in Figures 9 and 12. Besides, the incidence against the airfoil slightly increased due to the reduced solidity, which is believed to have only a minor effect on the boundary layer development on the suction surface.

### 3. NUMERICAL SIMULATION

#### 3.1 Flow Solver

The flow solver used in this study is a well proven in-house LES code with great accuracy in time and space that was originally developed by one of the authors (Yamada). The code is able to deal with multi-blocked computational grid system taking advantage of MPI (Message Passing Interface). A fourth-order central compact scheme is implemented as the scheme of least numerical viscosity, with the usage of filtering of 10-th order accuracy for securing numerical stability. The viscous fluxes are evaluated by the second-order central difference along with the divergence theorem. The standard Smagorinsky model is employed as subgrid scale turbulence model with van Driest dumping function, where Smagorinsky constant is 0.1.

#### 3.2 Computational Grid System

Figure 5 shows the computational grid for S-15 solidity case, where every 10-th line is shown. Note that the span of the computational domain was set to be 10% of the axial chord length. The grid system was composed of more than 40 subdomains with H-type sub-grids for the sake of achieving the orthogonality of the grid lines on the blade surface, by use of Gridgen Ver. 15 (Pointwise). The present study examined two solidity cases and the grid systems used for these two cases differed from each other, as shown in Table 2. Great attention had to be paid to the streamwise grid resolution over the region on the suction surface where the separation bubble existed. In addition, relatively a large number of grid points were also allocated near the inlet boundary for minimizing the turbulence decay, otherwise the inlet turbulence quickly became weakened before reaching the blade leading edge.

**Table 2 Specifications of computational grids**

<table>
<thead>
<tr>
<th>Tested solidity case</th>
<th>S-15</th>
<th>S-25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>6.7millions</td>
<td>24millions</td>
</tr>
<tr>
<td>Suction surface</td>
<td>511</td>
<td>1421</td>
</tr>
<tr>
<td>Pressure surface</td>
<td>229</td>
<td>677</td>
</tr>
<tr>
<td>Pitch direction</td>
<td>199</td>
<td>241</td>
</tr>
<tr>
<td>Span direction</td>
<td>39</td>
<td>49</td>
</tr>
<tr>
<td>Resolution (viscous wall units)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow direction (\Delta z^+)</td>
<td>&lt;11.0</td>
<td>&lt;2.75</td>
</tr>
<tr>
<td>Upstream of the separation point</td>
<td>&lt;7.8</td>
<td>&lt;2.75</td>
</tr>
<tr>
<td>Downstream of the separation point</td>
<td>&lt;6.41</td>
<td>&lt;5.10</td>
</tr>
<tr>
<td>Minimum spacing on the surface (\Delta \eta^+)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
3.3 Boundary Conditions

All flow quantities, except inlet velocity magnitude, were specified on the inlet boundary using the experimental data for \( Re_\text{e} = 5.7 \times 10^5 \), while the mass flow rate was adjusted on the outlet boundary to meet the continuity constraint. Since the flow solver was for compressible flow analysis, the stiffness problem made it very difficult for the solver to deal with the low-speed (strictly speaking, very low-Mach number) condition the present experiment encountered. The countermeasure taken against it was to increase the inlet velocity in the calculation by a factor of 10 from the measured value, while all geometries were accordingly scaled down so as to keep the Reynolds number the same as that of the experiment. This action changed the exit Mach number from about 0.026 to 0.26 in the calculation, which means that the simulated flow was still within incompressible flow regime and therefore the flow pattern was expected to remain substantially unchanged even with the increased inlet Mach number. Non-slip condition was applied on the blade surface and the periodic boundary conditions were imposed on the rest of the boundaries except inlet and outlet boundaries.

One of the important points that had to be dealt with in LES analysis was to specify inlet turbulence at the inlet in order to emulate the relevant experiment. The procedure employed in this study is given in the following.

3.4 Representation of Inlet Turbulence

3.4.1 SNGR Method

A brief explanation is given on how to create inlet turbulent flow field in the present study. The idea taken was to use homogeneous isotropic turbulence field created by SNGR (Stochastic Noise Generation and Radiation) method [14] [15].

A turbulent velocity vector can be expressed by using random Fourier decomposition as follows;

\[
\mathbf{u}_n(x) = 2 \sum_{k=1}^{\infty} \hat{u}_k \cos(k_x \cdot x + \psi_n) e^{i k_z n},
\]

where

\[
\hat{u}_k = \sqrt{E(k)} \Delta k
\]

\[
k_\alpha = [k_x, k_y, k_z] = [\cos \varphi_\alpha \sin \theta_\alpha, \sin \varphi_\alpha \sin \theta_\alpha, \cos \theta_\alpha],
\]

\[
k_\alpha' = [k_x', k_y', k_z'] = \frac{1}{\sqrt{3}} [k_x - k_y, k_y - k_z, k_z - k_x]
\]

and \( E(k) \) is a turbulent energy spectrum. \( \psi_n \) is a phase lag. Two angles \( \varphi_\alpha \) and \( \theta_\alpha \) are azimuth angle and the supplement of elevation angle of the wave number vector \( \mathbf{k}_\alpha \), respectively. The unit vector \( \mathbf{k}_\alpha' \) for n-th mode satisfies \( \mathbf{k}_\alpha \cdot \mathbf{k}_\alpha' = 0 \) so that the equation of continuity holds for these velocity vectors. All angles appearing in the above are random variables determined by probability density functions as shown in Table 3.

The energy spectrum \( E(k) \) can be expressed using von Kármán-Pao relationship as follows;

\[
E(k) = \alpha \frac{2/3 k_\alpha^2}{k_\alpha^4} \left[ 1 + (k_\alpha^2)^{-3/2} - (k_\alpha^2)^{-1} \right],
\]

\[
K = \int_0^\infty E(k) dk,
\]

where \( \alpha \) is Kolmogorov constant (=1.45276), \( K \) is total turbulence kinetic energy, \( k_\alpha \) is Kolmogorov wave number. The parameter \( k_\alpha \) determines the shape of the energy spectrum and is given by use of turbulence length scale \( L \) as follows:

\[
k_\alpha = \frac{2\pi}{L},
\]

The total turbulence kinetic energy \( K \) can be given by the following expression,

\[
K = \frac{3}{2}(T_{u_n} U_n')^2,
\]

where \( T_{u_n} \) was inlet turbulence intensity.

| Table 3  Probability density used to create random variables |
|-----------|-----------------|
| \( \varphi_\alpha \) = \( 1/2 \pi \) | \( 0 \leq \varphi_\alpha \leq 2\pi \) |
| \( \psi_n \) = \( 1/2 \pi \) | \( 0 \leq \psi_n \leq 2\pi \) |
| \( \theta_\alpha \) = \( \sin \theta_\alpha \) | \( 0 \leq \theta_\alpha \leq \pi \) |
| \( \alpha_\alpha \) = \( 1/2 \pi \) | \( 0 \leq \alpha_\alpha \leq 2\pi \) |

Figure 6 Homogeneous turbulence velocity vector field (top) and Implementation of the turbulent flow field into the computational domain (bottom)

3.4.2 Impose Turbulent Flow Field

Figure 6 illustrates the SNGR-originated homogeneous turbulence velocity vector field as well as the computational domain into which the turbulence picked up on the moving plane in the turbulence field was cast from the inlet boundary. The turbulent flow domain extended over 22 times axial chord length, one blade pitch and 10% axial chord length in the axial, tangential and spanwise directions, respectively. The plane moved at a speed of the inlet axial velocity in one direction until the plane reached one end of the turbulent flow domain. Then the plane reversed toward the other end of the domain. This means that the turbulence velocity data used as inlet boundary condition inherently featured cyclicity in time and were not completely random data.
As clearly seen in Figure 6 showing the vorticity magnitude contours, the inlet turbulence became weakened seemingly faster because of the numerical viscosity than would be expected to decay in a real situation. Since this was inevitable no matter how accurate the scheme was, trial-and-error adjustment was exercised to find out a suitable value of the inlet turbulence intensity $Tu_\infty$ so that the calculated turbulence intensity near the airfoil leading edge almost matched the measured value.

### 3.5 Code Validation

Figure 7 shows the static pressure distribution around the airfoil and stagnation pressure loss distribution measured for S-15 and S-25 cases with TG16 grid and without the turbulence grid in comparison with the LES predictions. As for the static pressure distribution, some discrepancies can be identified between the measurements and the calculations especially for no grid case, which was due to the existence of small but non-negligible background turbulence in the experiment. It is also clear from the measurement of loss distribution that the enhancement of freestream turbulence resulted in the loss reduction for S-15 case, while this was not the case for the higher blade loading case (S-25). Note that loss coefficients of negative value appeared in the blade-to-blade passage, which can be attributed to slight non-uniformity of inlet stagnation pressure. The calculations successfully reproduced these effects. Figure 8 illustrates velocity profiles measured around the separation region at S-15 aerodynamic loading condition, in comparison with the calculations. As appeared in Figure 7, the calculation of no grid condition exhibited overestimated the separation bubble, clearly because inlet freestream turbulence was not taken into account there. In contrast, the case using SNGR method to create the inlet freestream turbulence successfully reproduced the measured velocity profiles. To conclude, the code performance was very satisfactory in predicting at least time-averaged behaviors of the transitional behavior of the separated boundary layer, regardless of the airfoil loading.

Figure 9 shows several profiles of calculated RMS (Root-Mean-Squared) value of streamwise velocity fluctuation and the measured RMS value of the velocity fluctuation, which were all obtained before the separation point extending from $x/C_a = 0.50 \sim 0.65$ for S-15 case using TG16 turbulence grid. Note that the abscissa of this plot is RMS value normalized with local edge velocity, while the ordinate of this plot is the distance from the wall normalized with time-averaged local displacement thickness. Although the calculated profiles did not fully agreed with the measurements, they successfully captured several important features of the measured RMS values, such as the maximum of the RMS value that appeared inside the boundary layer and tended to increase towards the streamwise direction. The calculation also produced the RMS values outside the boundary layer that were close to the measured values. This means that the
numerical approach to create inlet turbulence using quasi-isotropic turbulence and adjust it so as to match the measured value near the leading edge was a reasonable one, despite the fact that there remains much about the management of inlet turbulence in LES analysis.

4. RESULTS

4.1 Time-averaged characteristics

Figures 10 and 11 show time-averaged velocity contours and RMS velocity fluctuation contours around the separation region for three different freestream turbulence cases at S-15 HL condition. Note that in Figure 11 there are several small circles along the center of each of the shear layers, which is to indicate the positions where FFT (Fast-Fourier Transform) analyses were made on velocity data (details will be discussed later). Integral boundary layer properties such as displacement and momentum thicknesses for S-15 solidity condition are also shown in Figure 12. These three figures clearly demonstrate the intense impact of the inlet freestream turbulence on the suction-side boundary layer, in particular on the separation bubble, resulting in the reduction of the size of the separation bubble in the time-averaged flow field. Interestingly, the momentum thickness near the trailing edge measured for TG16 case became smallest among the three cases, implying a possibility of profile loss reduction due to freestream turbulence. Besides, RMS contour for TG16 case reveals that the shear layer associated with the separation bubble was energized just after the separation point appearing around $x/C_{ax} = 0.5$.

Figure 13 represents velocity contours of S-25 UHL2 solidity condition for no grid and TG16 cases. The peak height of the separated bubble appeared around at $x/C_{ax} = 0.73$, which almost coincides with the pressure recovery point identified in $C_f$ distribution in Figure 4. As mentioned in the discussion of static pressure distributions around the airfoil, the separation bubble for S-25 case was much shorter than that of S-15 case. In addition, the peak height of the separation bubble became small in comparison with Figure 10, probably because the intense diffusion in this case enhanced the instability of the shear layer, leading to earlier reattachment of the separation bubble before its full growth.

In TG16 case, the peak of the separated bubble moved upstream, while the height of the separated bubble remained almost unchanged in spite of the enhanced freestream turbulence.

4.2 Frequency Analysis

This section discusses the unsteady characteristics of the separation bubble subjected to inlet freestream turbulence, comparing them with those of no grid condition. HL Condition Figure 14 illustrates the results of FFT analysis of the velocity data acquired along the centerline of the shear layer as shown in Figure 11 for the three FST conditions. Note that the ordinate of each of the plots is expressed in a linear scale. Figure 14(a) represents the spectrum for the lowest FST condition, showing that there were two frequencies, i.e., 200Hz and 380Hz, at which the spectrum exhibited the peak. The other peak also appeared around 600Hz, which was due to the blower impeller having 12 blades and rotating at 2950rpm.
Time-averaged displacement and momentum thicknesses for three different inlet turbulence cases at $S_{15}$ solidity condition.

Figure 13. Velocity contours measured for two different freestream turbulence cases at $S_{25}$ solidity condition.

Two different transition modes of the boundary layer were likely to induce the flow events that led to those peaks. One of the modes is Tollmien-Schlichting (T-S) wave, and the other is Kelvin-Helmholtz (K-H) instability wave. As for the former mode, Walker [14] proposed the following correlation to predict the T-S wave frequency of maximum amplification rate for pre-separated boundary layer,

$$\frac{2\pi f_{\text{max}}}{U^2} = 3.2 \text{Re}_{\delta}^{-\frac{1}{2}}. \quad (17)$$

For the discussion of K-H instability, the criterion of Chandrasekhar [16] seems useful, which says that K-H instability wave can happen when the following condition is met,

$$0 < kh < C. \quad \quad (18)$$

where $k$ is the wave number of instability wave and $h$ is the characteristic length of the shear layer. The constant $C$ is the upper limit of unstable region of K-H instability, which is 1.2785 for a shear layer with a linear velocity profile (LVP) or 1 for a tanh-like profile (TVP). Assuming that the phase velocity of the instability wave $U_{\text{shear}}$ can be approximated by a half of the freestream velocity, along with the relationship,
\[ kU_{\text{shear}} = 2\pi \frac{U_{\text{shear}}}{\lambda} \approx 2\pi f_{\text{shear}}, \] (19)

one can obtain the following expression,
\[ 0 < f_{\text{shear}} < \frac{C_{\text{U}}}{2\pi h} \] (20)

It follows from Eq. (17) using the experimental values measured near the separation point that if there is evaluated to be 213 Hz, which is close to the frequency of the first peak in Figure 12. In the meantime, since \( h \) can be approximated by the shear layer thickness, which was about 0.002 m, and \( U_{\text{shear}} \) was about 5 m/s, Eqs. (18) and (19) therefore yield \( 0 < f_{\text{shear}} < 509 \) [Hz] for LVP shear layer and \( 0 < f_{\text{shear}} < 398 \) [Hz] for TVP shear layer. This means for both velocity profiles that the two peaks were likely to be associated with K-H instability wave. In fact, as will be shown later, LES analyses revealed that the second peak came from K-H instability wave. Roberts and Yaras [17] mentioned a possibility that T-S wave triggers K-H instability wave on the separated shear layer, which eventually leads to the transition of the separated boundary layer. In the present study, there have been obtained very few evidences that show the direct relationship between T-S wave and K-H wave in the course of the transition of the boundary layer.

Figures 14(b) and (c) display spectrum amplitudes obtained at the enhanced freestream conditions. It is clear that the effect of the inlet freestream turbulence appeared before the separation point and the growth rate of the spectrum amplitude was larger than that of no grid case shown in Figure 14(a), while the peak frequencies observed in no grid case cannot be clearly seen in these figures.

**UHL2 Condition** Figure 15 shows spectrum amplitudes of the velocity fluctuations for low freestream and enhanced freestream turbulence test cases at UHL2 condition (S-25). Comparing the bottom of Figure 16 with Figure 15, for example, it turns out that the growth rate of the spectrum amplitude at UHL2 condition was much larger than that of HL condition. Although the spectra for no grid condition featured rather complicated peak distribution, the peaks appeared, in an obscure manner, around at 220 Hz and 380 Hz. According to the previous discussion, it is quite likely that the latter peak is induced by K-H instability wave.

### 4.3 Results of LES Analyses

#### 4.3.1 Unsteady Behavior of the Shear layer

**HL condition** Figure 16 illustrates the results of LES analyses in terms of spanwise vorticity (left) and velocity magnitude with streamlines for S-15 solidity condition with no turbulence grid. This figure shows the sequence of vortex shedding from the shear layer including rolling up of the shear layer, breakdown of the shed vortex and re-rolling up. Each of the plots in this figure is indexed with non-dimensionalized time \( \tau \), where the time-scale used here was the axial chord divided by the inlet sonic speed (recall that the code used was basically for solving compressible flow). In step 1 at \( \tau = 6.0 \), the separated shear layer rolled up to become a vortical structure marked as A, which was characterized by cat’s eye streamline. This structure was stretched out toward the downstream (step 2), followed by the division into two parts called A1 and A’ (step 3). A1 was a shed vortex from the shear layer, which was advected downstream experiencing vortex breakdown (step 4), while A’ started to roll up at \( \tau = 8.4 \).

For the enhanced freestream turbulence case shown in Figure 17, the process of vortex formation, shedding and advection was more complicated than that observed for no grid condition. A vortical structure indexed as A rolled up at \( \tau = 1.2 \) (step 1), which was released from the separated zone at \( \tau = 1.8 \) (step 2). At that moment, another vortical structure marked with B tended to form itself. The vortical structure A was then advected experiencing breakdown at \( \tau = 2.6 \) (step 3), while the structure B was stretched and collapsed into B1 and B2 before taking a shape of vortex.

**UHL2 condition** As already seen in the velocity contours of Figure 13, for example, the transition of the separation bubble to turbulence started earlier at UHL2 condition than at HL condition. This can be reconfirmed by looking at the location where the roll-up of the shear layer happened. Figure 18 indicates that the vortical structure A, which formed clear and comparatively large cat’s eye flow pattern at the downstream of the separation bubble at \( \tau = 9.6 \). After the structure A was shed from the shear layer and started to grow at \( \tau = 10.6 \), another vortex-like structure marked with B appeared accompanied with clear cat’s eye pattern. In step 3 at \( \tau = 11.8 \), the structure A was about to break down around at \( x/C_{\text{m}} = 0.8 \), while the vortex B was elongated and eventually divided into two parts, B1 and B2 at \( \tau = 13.4 \). These two vortex-like structures, particularly B2 could not hold their shape before they reached \( x/C_{\text{m}} = 0.8 \) (see in step 5 at \( \tau = 14.8 \). The
behavior of the separation bubble mentioned here seems to explain the reason for the appearance of several peaks in the spectra in the top of Figure 14.

Figure 19 depicts a similar flow field with Figure 18 except for the level of freestream turbulence. It is evident from this figure that the breakdown of shed vortices happened much faster than that of no grid condition. For instance, the shed vortex A in this case tended to lose its attribute as vortex before reaching $x/C_{ax} = 0.8$ in step 2 at $t^* = 13.4$, which can be confirmed by the cat’s eye flow pattern that was fading away prior to $x/C_{ax} = 0.8$. This rather rapid loss of the organized structure seems to give an explanation for the disappearance of dominant peaks in the spectrum amplitudes shown in the bottom of Figure 15.

Table 4 Data of K-H instability waves observed in LES analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>$f_{shear}C_{ax}/U_{in}$</th>
<th>$k$ ($= 2\pi/\lambda$)</th>
<th>$h$</th>
<th>$kh$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-15 no grid</td>
<td>6.986</td>
<td>49.1/$C_{ax}$</td>
<td>0.018</td>
<td>0.884</td>
</tr>
<tr>
<td>S-15 TG16</td>
<td>7.606</td>
<td>56.1/$C_{ax}$</td>
<td>0.018</td>
<td>0.959</td>
</tr>
<tr>
<td>S-25 no grid</td>
<td>8.363</td>
<td>61.3/$C_{ax}$</td>
<td>0.018</td>
<td>0.975</td>
</tr>
<tr>
<td>S-25 TG16</td>
<td>8.532</td>
<td>61.4/$C_{ax}$</td>
<td>0.018</td>
<td>0.992</td>
</tr>
</tbody>
</table>

4.3.2 Discussion on K-H Instability

Table 4 summarizes numerical data related to K-H instability wave which are roughly extracted from the above-mentioned velocity profiles and sequential plots that showed the vortex formation and shedding from the separated shear layer. Since the vortical structure marked as A was assumed to be directly connected with K-H instability, the distance between the two centers of neighboring cat’s eye patterns associated with the structure A was regarded as the wave length of K-H instability wave $\lambda$. Dividing the phase velocity $U_{shear}$ with $\lambda$, the frequency of K-H instability wave $f_{shear}$ was evaluated, as shown in Table 4 in a non-dimensional fashion.

It follows from these data that the criterion of $kh < 1$ was met for all four test cases. This means that the process of vortex formation and shedding numerically reproduced in this study was closely connected with K-H instability wave, as mentioned in the previous section. Note that some caution seems necessary to the case of S-25 with TG16 turbulence. In consideration of the rough estimation of $h$ or $k$, it was quite likely that $kh$ for that case might have exceeded unity for that case. This possibility may also explain to some extent the features of the spectra shown in the bottom of Figure 16. Besides, the frequency clearly identified in the experiment was 380 Hz, which can be non-dimensionalized as $f_{shear}C_{ax}/U_{in} = 7.6$. This value almost matches the numerically predicted values.

5. CONCLUSIONS

This study conducted detailed hot-wire probe measurements of the boundary layer on the Ultra-High lift and High Lift low-pressure turbine airfoils for aero-engines. LES analyses were also carried out using artificial inlet freestream turbulence created by SGNR method. The main focus of the study was on the effects of freestream turbulence as well as airfoil loading on the behavior of the separation bubble, in particular on transitional process via T-S wave or K-H instability wave. Key findings through this study are as follows;

I. Discussion on time-averaged characteristics of the separated boundary layers revealed that the freestream turbulence had a significant impact on the separation bubble in various ways.

1. At HL condition, the peak height of the separation bubble lowered and its streamwise position moved upstream as the freestream turbulence increased, implying earlier transition of the separated shear layer to turbulence and reattachment. The momentum thickness near the trailing edge for TG16 case edge became smaller than that of no grid case. This indicated a possibility of aerodynamic loss reduction with freestream turbulence.

2. At UHL2 condition, the enhanced freestream turbulence affected the transitional behavior of the shear layer so seriously that the transition occurred rather abruptly, while the peak height of the separation bubble almost unchanged.

II. Frequency analyses of the velocity data measured in the middle of the shear layer found out temporal characteristics of the separation bubble subjected to the influence of freestream turbulence.

1. At HL condition, two dominant peaks were observed for no grid case. The lower peak frequency almost agreed with T-S wave frequency of maximum amplification rate predicted by use of Walker’s correlation (Eq. (17)). The higher peak frequency met the criterion of K-H instability wave given by Chandrasekhar. In addition, there was no clue showing the connection between T-S wave and K-H instability wave in the process of shear layer transition. For larger freestream turbulence cases, the peak that could be attributed to T-S wave did not appear in the spectra and the peak due to K-H instability wave became vague.

2. At UHL2 condition, the spectrum amplitudes exhibited complicated peak frequency distributions. At the same time, the growth rate of the amplitudes became much larger than that of HL condition. It was clear that the enhanced freestream turbulence promoted transition of the separated shear layer, which was consistent with the time-averaged velocity data.

III. LES analyses were carried out to illustrate unsteady behavior of the separation bubble, including formation, shedding, advection and breakdown of the vortical structure from the shear layer. The freestream turbulence as well as airfoil loading made the transitional behavior rather complicated one, which was accompanied with aperiodic vortex shedding and prompted vortex breakdown. Moreover, the LES analysis adequately predicted the frequency of K-H instability wave.

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REFERENCES


Figure 16  LES analysis showing the sequence of vortex shedding from the shear layer with no grid case (S-15).
STEP1 A: Separated shear layer rolls up. \( t^* = 1.2 \)

STEP2 A: Shed. B: Separated shear layer rolls up \( t^* = 1.8 \)

STEP3 A: Adveceted and broken down. B: Stretched \( t^* = 2.6 \)

STEP4 B: Divided into B1 and B2. B1 and B2: Adveceted \( t^* = 3.6 \)

STEP5 B1, B2: Adveceted and broken down. A': Rolls up \( t^* = 4.4 \)

Figure 17 LES analysis showing the sequence of vortex shedding from the shear layer with grid TG16 (S-15).
**STEP1**  
A : Separated shear layer rolls up ($t^* = 9.6$)

**STEP2**  
A : Discharged. B : Shear layer rolls up ($t^* = 10.6$)

**STEP3**  
A : Advec ted and broken down. B : Stretched ($t^* = 11.8$)

**STEP4**  
B : Divided into B1 and B2. B1 ($t^* = 13.4$)

**STEP5**  
B1 and B2: Advec ted and broken down. A': Rolls up ($t^* = 14.8$)

Figure 18  LES analysis showing the sequence of vortex shedding from the shear layer with no grid (S-25).
Figure 19  LES analysis showing the sequence of vortex shedding from the shear layer with grid TG16 (S-25).