Assessment of the Influence of Boundary Layer Ingestion (BLI) on the Axial Fan

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Abstract. Boundary Layer Ingestion (BLI) is a technology which is effective to reduce fuel consumption of future commercial aircrafts. However, the inlet distortion caused by BLI has a negative on the engine performance. This paper investigates the effect of the inlet total pressure distortion on the aerodynamic performance of the fan rotor. Unsteady numerical analysis was conducted on JAXA TechClean Fan with circumferential distortion caused by BLI. As the result, under the high distorted condition, the peak efficiency of the rotor decreases by 0.622 points. It is found that the main factor of the efficiency reduction is tip-wall passage vortex.

1. Introduction

In recent years, the demand for air transportation keeps increasing and considering the environmental impact and fuel costs is an important issue. To address this issue, NASA has set strategic goals in noise, emissions, and performance of fuel burn and conducted case studies of foster advanced aircraft concepts [1]. Boundary Layer Ingestion (BLI) is one of the most effective technologies for reducing fuel consumption proposed.

BLI achieves the reduction of fuselage drag and improvement of fuel efficiency by embedding engines on the aircraft and ingesting the boundary layer on the airframe. A theoretical explanation is given by Drela’s power balance method [2]. Figure1 shows a schematic diagram of applying the method to 2-D airfoil. In this figure, two types of engine locations are compared. One is the isolated propulsor model that an engine is placed away from the airfoil representing conventional configuration. The isolated propulsor power \( P_{\text{isolated}} \) under the cruising condition is given by the following equation.

\[
P_{\text{isolated}} = \Phi_{\text{surface}} + \Phi_{\text{wake}} \tag{1}
\]

In this equation, \( \Phi_{\text{surface}} \) and \( \Phi_{\text{wake}} \) denotes the dissipations by the airfoil surface boundary layer and by wake respectively. The other is the wake-ingesting propulsor model in which an engine located behind the airfoil ingest the boundary layer flow. Assuming that the wake-ingesting propulsor ingests the wake and re-energize it perfectly, \( \Phi_{\text{wake}} = 0 \) and the power of the wake-ingesting propulsor \( P_{\text{ingest}} \) is

\[
P_{\text{ingest}} = \Phi_{\text{surface}} \tag{2}
\]

Comparing equation (1) and (2), the wake-ingesting propulsor model saves \( \Phi_{\text{wake}} \) and reduces fuel consumption.
On the other hand, BLI engine always experiences inlet total pressure distortion caused by boundary layer and the fan adiabatic efficiency may decrease. Therefore, understanding the mechanism of performance deterioration and dealing with the total pressure distortion are required. Horimoto et al. [3] conducted an unsteady numerical analysis on Rotor67 simulating several types of distortion. They show the region leaving the distorted sector shows the highest Mach number which induces boundary layer separation and generates additional loss. Gunn et al. [4] performed a numerical simulation using subsonic and transonic fans simulating Silent Aircraft Intake distortion profile and the performance deterioration are explained by diffusion factor. William et al. [5] designed a distortion-tolerant fan for a high-bypass ratio boundary-layer ingesting propulsion system and conducted wind tunnel test.

In this paper, a series of numerical analysis result of the TechClean fan (advanced configuration) developed by JAXA is shown under the clean and distorted inflow conditions.

2. Numerical Method

2.1. Numerical scheme

The overview of the CFD scheme is shown in Table 1. UPACS on Supercomputer System generation 2 (JSS2), which is a CFD solver developed by JAXA, is used for three-dimensional unsteady numerical simulations. The analysis is conducted with RANS. The grid is a hybrid grid using O-Grid and H-Grid and the time interval is set so that one rotation of the rotor would be 16000 steps. The computational domain extended for 1.5 times chord upstream and downstream of the rotor. Around 1.27 million cells were used per rotor and the total number of cells for full-annulus grid was 23 million. The distortion was simulated by giving the total pressure distribution to the inlet boundary.

| Governing equation | Reynolds-averaged-Navier-Stokes |
|-------------------|---------------------------------|
| Turbulence model  | Spalart-Allmaras                 |
| Time iteration method | MFGS (Matrix Free Gauss Seidel) |
| Convective term   | Roe Scheme                      |

2.2. TechClean fan (advanced configuration)

A rotor part of TechClean fan (advanced configuration) was chosen for this analysis. This fan was designed as a part of JAXA TechClean project which aims to suppress noise level, reduce exhaust gas emission and decrease CO2 [6].
Table 2. Specifications of TechClean fan (advanced configuration).

| Specification                      | Value          |
|------------------------------------|----------------|
| Diameter of blade                  | 500mm          |
| Number of blades                   | 18             |
| Design mass flow rate              | 34.5kg/s       |
| Design rotational speed            | 15135rpm       |
| Design total pressure ratio (rotor)| 1.7            |
| Rotor efficiency                   | 92%            |
| Hub/Tip ratio                      | 0.311          |
| Tip relative Mach                  | 1.3            |
| Tip clearance                      | $5 \times 10^{-1}$ mm |

3. Distortion Profile

In order to apply a distortion profile, the result of CFD analysis simulating the experiment described hereafter was referenced. The authors conducted wind tunnel test using an engine-airframe integrated model whose airframe sectional shape is the NACA0012 to confirm the effects of BLI [7]. The test was conducted in JAXA’s 65 $\times$ 55 cm low turbulent wind tunnel. A photograph of the test model installed in the wind tunnel and a schematic of the model are shown in figure 3 and 4 respectively. A 90 mm diameter ducted fan engine was embedded on the upper aft surface of the NACA0012 airfoil model and the engine ingests the boundary layer flow on the airframe surface. Therefore, the lower portion of the engine always experiences total pressure distortion. The total pressure profile was obtained using a pilot rake moved by 2-axis traverse devise. A CFD analysis was performed simulating the experiment [8]. In this study, to use the high-density data, the result of the CFD analysis was adopted. The total pressure distribution at the aerodynamic interface plane (AIP) which is upstream of the rotor and downstream of the intake was obtained and the giving to the inlet boundary of this analysis.

Figure 3. Wind tunnel experiment [7].

Figure 4. Wind Tunnel test model with BLI propulsor [7].

Figure 5. Total pressure profile.

Table 3. Simulation Condition

| Condition | Average total pressure in entrance | Maximum distortion intensity at Ring 5 |
|-----------|-----------------------------------|---------------------------------------|
| Clean     | 101.325 kPa                       | -                                     |
| BLI1      | 101.243 kPa                       | 0.0185                                |
| BLI2      | 99.35 kPa                         | 0.0293                                |
Since the diameter of the fan used in the test is different from the TechClean fan, the distortion intensity may be different. Then, two types of distortion intensity were used in this analysis as shown in Table 3 (BLI1, BLI2). Circumferential Distortion Intensity ($\Delta P_C/P$), is used to represent the magnitude of the distortion according to SAE ARP 1420B [9]. This evaluation index is calculated by the following formula using total pressure obtained at the rakes circumferentially arranged at a certain radius (Ring). The value calculated at radius ($r = 0.237$ m) are shown in Table1. $P_{AV}$ and $P_{AVLOW}$ represent the Ring Average total pressure and the Ring Average total pressure of low total-pressure region for a ring respectively. In addition, for comparison purpose, the analysis was also performed under a uniform flow condition without distortion (Clean).

\[
\left(\frac{\Delta P_C}{P}\right)_i = \left(\frac{P_{AV} - P_{AVLOW}}{P_{AV}}\right)_i
\]  

(3)

4. Result and Discussion

4.1. The result of clean analysis

Figure 6 shows the characteristic curve obtained from the clean analysis. The horizontal axis is the relative corrected mass flow that normalized by the choked flow. The total pressure ratio has a good agreement with experiment data on the low mass flow rate especially. On the high mass flow rate, the analysis result of total pressure ratio tends to be lower than the experimental result. The overall trend seems to be able to represent the characteristics of TechClean fan.

![Figure 6. Total pressure ratio under clean condition.](image)

4.2. The result of BLI analysis

4.2.1. Comparison of characteristic curve. Figure 7 shows the comparison of the characteristic curves under clean conditions and BLI conditions. Mass averaging is used to calculate the total pressure and temperature of upstream and downstream of the rotor. According the graph, comparing the total pressure ratio at the same corrected flow rate, the total pressure ratio of the BLI condition appears higher than that of the clean condition. This may be because the specific work increases due to the decrease of the mass rate at tip side for the BLI case. In other words, the performance of the tip side shifts to the lower flow rate side. BLI2 has the lower total pressure ratio compared to BLI1. This indicates higher distortion intensity of BLI2 compared to that of BLI1 causes the negative effect on the fan performance.

When comparing the adiabatic efficiency, BLI2 has the lowest peak efficiency (PE), which is $0.622$ points lower than the clean condition. Compared with BLI1, BLI2 has lower total pressure ratio and lower efficiency, suggesting that relatively strong distortion may cause performance degradation.
4.2.2. Flow field analysis. Figure 8 shows the instantaneous relative Mach number at 90% span position at the peak efficiency point of BLI2. In the center of the figure, there is a distortion region where the axial flow velocity and the relative Mach number decrease due to the total pressure drop by simulating the boundary layer. The rotor blade moves from left to right, and the left side in the figure is the area before the distortion and the right side is after the distortion. The shock structure is changing through the rotor because the flow velocity and the inflow angle are different at each blade position. Now, look at figure 8 from left to right. In region A, a passage shock occurs between the blades as seen in the choke condition under clean condition. In region B (distortion region), the passage shock gradually moves to the upstream and finally the detached shock is generated at the tip as seen in the near-stall condition with low mass flow rate. After the blade passes though the distortion area (region C), the detached shock wave gradually moves downstream, and the flow field returns to the choke condition as in region A. This change in one rotation due to the distortion causes the variation of blade load.

Figure 9 shows the rotor work input because the total enthalpy upstream of the rotor is constant. The work gradually increases in the distortion region and the peak locates near the end of the distortion region. The work decreases in the region C, and gradually returns to the original level. In summary, in the case of circumferential distortion, there is a high-load region near the exit of the distortion region where the work of the blade increases significantly. It is found that the location of the high-load region corresponds to the location where the shock wave structure is similar to the near-stall condition.

Figure 8. Instantaneous relative Mach number at 90% span position at the PE (BLI2).
Figure 9. Work input \((h_{out} - h_{in})/U_{90\%}^2\).

4.2.3. Loss generation. Figure 10 shows the entropy distribution at the 90% span position at the highest efficiency point of BLI2. Entropy is calculated by the equation (4).

\[
S - S_0 = C_p \ln \frac{T}{T_{ref}} - R \ln \frac{P}{P_{ref}}
\]  

(4)

The center of figure 10 is the high entropy region due to the distortion. It should be noted that the distortion region originally has high entropy and not all downstream entropy is generated by rotor because the total pressure is low, and the total temperature is constant at the boundary condition. At the high-load region near the exit of the distortion region, the loss increases due to the detachment shock wave. However, the amount of entropy produced is relatively small and it suggests that it is not a major factor of the decrease in BLI2 efficiency.

Figure 10. Entropy distribution at 90% span position at the PE (BLI2).

Figure 11 shows the relative Mach number distribution, and figure 12 shows the entropy distribution at 96% span position. The periodic changes in the flow field qualitatively agree with figure 8. The detached shock wave which is seen at stall point is also conformed in the exit of distortion. In particular, a separation occurs in this area. The entropy distribution also indicates that loss increases significantly in the high load region.
Figure 11. Instantaneous relative Mach number at 96% span position at the PE (BLI2).

Figure 12. Entropy distribution at 96% span position at the PE (BLI2).

Figure 13. Entropy distribution downstream of the rotor

Figure 13 shows the entropy distribution downstream of the rotor. The high entropy region is seen near the casing in BLI2. It indicates that the main factor that caused the reduction of the efficiency by 0.622 points in BLI2 is the casing.

There are two main causes of the loss that occurs in the casing. One is the tip-leakage vortex and the other is the tip-wall passage vortex on the casing surface by the rotor blade. In order to identify the cause of the loss in the casing, the leakage flow rate from the tip clearance is compared under clean condition and BLI2 condition. The leakage rate to mass flow rate was 0.715 points under Clean condition and 0.686 points under BLI2 condition respectively, and there is no significant difference between these two conditions. Hence, the leakage from the tip clearance is not a main reason of the loss, and the tip-wall passage vortex increased by the distortion of BLI. The circumferential distortion by BLI periodically changes the rotor work input and forms a high-load region near the distortion exit. The axial velocity decreases in the distortion region because of the low total pressure. It is considered that when the flow is exposed to this high-load region, the flow cannot withstand the adverse pressure gradient and the separation occurs near the casing.
5. Conclusion

1. Unsteady analysis was performed for the JAXA TechClean fan the with the circumferential distortion assuming BLI.
2. As a result of the analysis, the adiabatic efficiency at the highest efficiency point is reduced by 0.622 points under the BLI2 condition compared to the clean condition.
3. Circumferential distortion changes the shock structure of the rotor blade periodically. When operating at the highest efficiency point, it moves from choke to stall repeatedly.
4. The detached shock wave moves to the upstream side near the region leaving the distorted sector, which is similar a near stall condition.
5. At the 90% span position, which is not affected by the casing, a slight increase in entropy is confirmed due to the strengthening of the detached shock wave in the high-load region. However, this is not a major factor in the decrease in efficiency. On the other hand, at the 96% span position which is close to the casing, remarkable loss occurs in the high load region. It is found that the main factor of the efficiency reduction is in the casing.
6. The effect of distortion on the amount of leakage from the tip clearance is small. This indicates that the tip-wall passage vortex is the main factor of the loss.
7. The low momentum fluid in the casing by the BLI cannot withstand the adverse pressure gradient. Flow separation occurs in the high-load region due to the circumferential distortion. This causes the performance degradation.

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