Proceedings of Global Power and Propulsion Society
ISSN-Nr: 2504-4400
GPPS Hong Kong 2023
October 17-19, 2023
www.gpps.global

GPPS-TC-2023-144

Influence of inlet and outlet geometrical angle deviations on the aerodynamic performance of compressor airfoil

Shenzhen Li
Xi'an Jiaotong University
1021678293@stu.xjtu.edu.cn
Xi'an, Shanxi, P.R.China

Haideng Zhang
Airforce Engineering University
zhanghaideng@126.com
Xi'an, Shanxi, P.R.China

Yun Wu
Airforce Engineer University
Xi'an Jiaotong University
wuyun1223@126.com
Xi'an, Shanxi, P.R.China

Enbo Sun
Xi'an Jiaotong University
sunenbo@stu.xjtu.edu.cn
Xi'an, Shanxi, P.R.China

Yuhan Long
Xi'an Jiaotong University
637170145@qq.com
Xi'an Shanxi, P.R.China

ABSTRACT

The geometric deviation of blades significantly impacts the performance of modern highly loaded compressors. Therefore, attention should be paid to the influence of the geometric deviation of blades on the aerodynamic performance of compressors. This paper intends to investigate the influence of inlet/out geometrical angle deviations on the aerodynamic performance of a typical subsonic controlled diffusion compressor airfoil. The aerodynamic performances of the compressor airfoil with different types of inlet/outlet geometrical angle deviations are simulated and the mechanism behind the variations of the total pressure loss as well as outlet deviation angle are analyzed. The blade becomes more sensitive to angle geometric deviation as the incidence angle increases, and the impact of angle deviation on aerodynamic performance is greater in the negative incidence angle range than in the positive ones. However, the influence of geometrical angle deviations at the inlet on blade aerodynamic performance is greater than that at the outlet. Geometrical angle deviation at the inlet alters the peak velocity and reverse pressure gradient during the acceleration process of depressurization at the suction surface of the blade, whereas geometrical angle deviation at the outlet directly changes the flow direction with geometric variation, and this has an impact on aerodynamic performance.

INTRODUCTION

As one of the three primary components of gas turbine engines, the compressor's aerodynamic performance is crucial to the engine's overall performance. (Cumpsty, 1989; Ballal and Zelina, 2004; Tubbs and H,1991)To achieve a higher pressure ratio and efficiency, the geometry of the compressor blade is designed to be more and more complicated. This makes it more difficult to manufacture the compressor blades accurately, and the cost of manufacturing compressor blades is estimated to account for 30% of the entire gas turbine engine. As a matter of fact, deviation from real compressor blades seems to be unavoidable owing to the complicated three-dimensional modeling, manufacturing, and installation process. For this reason, the aerodynamic performance of real compressor blades will differ from that of initially designed ones and this is detrimental to the development of gas-turbine engines

Numerous efforts have been made both domestically and internationally to quantify the geometric errors of blades and their effects on aerodynamic performance (Suder et al., 1995; Wheeler, Sofia, and Miller, 2009; Goodhand and Miller, 2011). Garzon et al. developed a set of methods using probability theory to quantify the impacts of geometric machining errors on the aerodynamic performance of compressor blades. The numerical simulation conducted on the elliptic leading edge established that it had a considerable effect on reducing the suction peak and enhancing the aerodynamic performance of the blade. Drawing from the idea of regulating excessive bending of the leading edge and blade, the author suggested a circular leading edge with a platform. This design has been shown to improve the blade's surface flow, thus achieving outcomes comparable to those of the elliptic front (Lu and Xu, 2000; Xu, 2003)The connection between the circular leading edge and the blade body is not smooth, which leads to the generation of separation bubbles in the proximity of the leading edge. This, in turn, causes an advanced transition and flow loss. (Liu, Li, and Jiang, 2002; Liu, Jiang, and Chen, 2004). Ensuring continuity in the curvature of the blade's leading edge can significantly inhibit the formation of a suction peak at the leading edge, and facilitate healthier development of the blade's surface layer. This, in turn, effectively enhances the properties of the blade (Song and Gu, 2013a; Song and Gu, 2013b; Liu, Yuan, and Yu, 2013c)The results demonstrate that the shape of the leading edge has a significant impact on the blade's profile. However, few studies have been made on the influence of geometrical Angle deviation at the inlet or outlet.

Inlet and outlet geometrical angle deviations are two commonly encountered compressor blade geometric deviations. it has been acknowledged that the aerodynamic performance of compressor airfoil is very sensitive to the variation of inlet/outlet geometrical angle deviations. Then This paper tries to find out the mechanism behind the influence of inlet/outlet geometrical angle deviations on the aerodynamic performance of compressor airfoil. The flow field of a typical controlled diffusion compressor airfoil with different inlet/outlet geometrical angles is numerically investigated, and the influence of inlet/outlet geometrical angles on the total pressure loss as well as the deviation angle of the compressor airfoil is analyzed in detail. The findings of this paper can be used to establish the correlation model between inlet/out geometrical angles and compressor airfoil aerodynamic performance variations.

METHODOLOGY

Compressor airfoil model •

The controlled diffusion compressor airfoil investigated in this paper is the 50% span section of a subsonic compressor stator blade. Table 1displays the detailed geometric and aerodynamic design parameters of the compressor airfoil.

Table 1 Design parameters of 1.5 stage compressor stator blade profile

Design parameter	Symbol	Value
Chord	C(mm)	48.77
Chord	Cax(mm)	41.82
Inlet Mach Number		0.55
Blade spacing	t(mm)	73.6
Inlet metal angle	β_1(deg)	50.38
Outlet metal angle	β_2 (deg)	16.8

As shown in Table 1, the design inlet/out geometrical angles of the compressor airfoil is 50.38° and 16.8° respectively. Referring to the distributions of compressor blade manufacturing deviations, the maximum inlet/out geometrical angle deviations of the compressor airfoil are set to be 0.6°. Definitions of the inlet/outlet geometrical angle deviations are shown in Fig 1. This paper mainly focuses on the mechanism behind the influence of inlet/outlet geometrical angle deviations on the aerodynamic performance of compressors. Then the numerical results of compressor airfoil aerodynamic performance with typical inlet/outlet geometrical angle deviations (±0.2°, ±0.4°, ±0.6°) are presented.

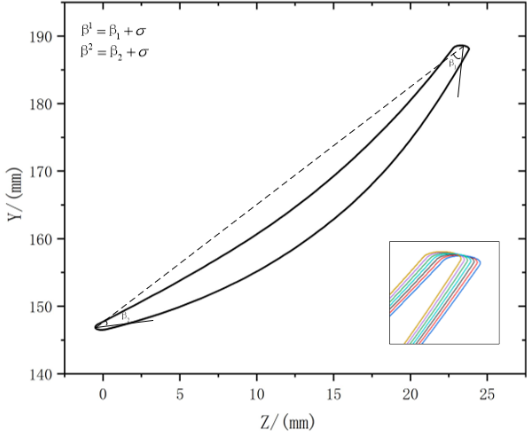


FIG 1 Schematic diagram of error profile of stator blades

Numerical method

The computation grid used in this paper is shown in Fig. 2, and the HOH topological structure is used. The inlet of the computation domain is 20% chord length upstream of the blade leading edge, and the total pressure boundary is used. The outlet of the computation domain is 30% chord length downstream of the blade trailing edge, and the static pressure boundary is used. During the simulation, the inlet total pressure and outlet static pressure is adjusted to ensure the inlet Mach number and the inlet flow angle is adjusted to change the incidence angle. As for the blade surface, the non-adiabatic and non-slip boundary is used, and along the pitch-wise direction, the periodic boundary is used. and capture the influence of inlet/outlet geometrical angle deviations on the aerodynamic performance of the compressor airfoil, local refinement was conducted at the leading/trailing, as shown in Figure 2. The total grid node number of the simulation domain is One hundred thousand, and the near-wall grid is refined to ensure y+ < 1.

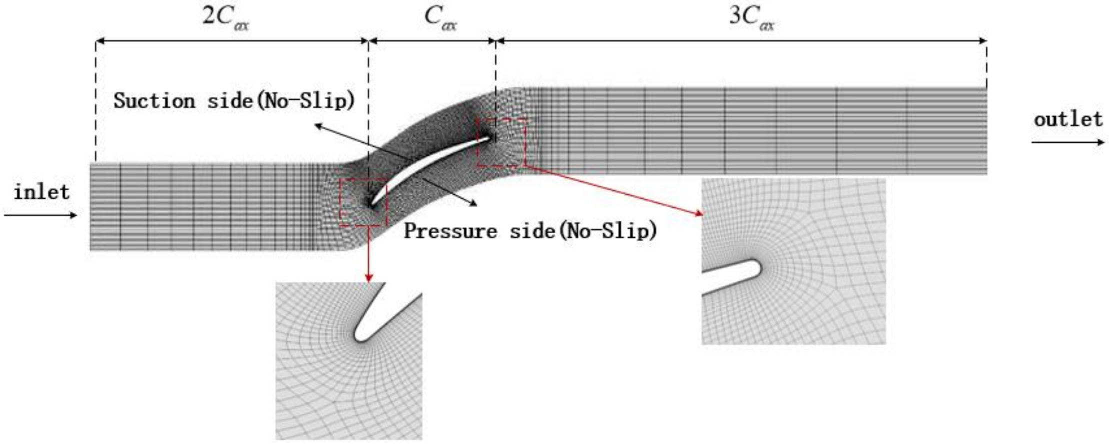


FIG 2 Computing domain diagram

The simulation calculations were conducted using Ansys CFX. The gas was modeled as an ideal gas, and the turbulence model selected was SST without transition, with second-order accuracy. Inlet turbulence was set at 1% for the corresponding conditions. A high-order solver with a step size of 1500 was used, and computational convergence was achieved when the residual error was less than 1.0×10^{-6}.

RESULTS ANG DISCUSSIONS

The total pressure loss coefficient and deviation angle are used to quantify the aerodynamic performance of the compressor airfoil.

The total pressure loss coefficient ω, is defined as

$$\omega = \frac{P_{t1} - P_{t2}}{P_{t1} - P_1} \qquad (1)$$

The relative variation of ω is used to analyze the variation of compressor airfoil total pressure loss coefficient, and defined as:

$$\omega\_\mathrm{ratio} = \frac{\omega_{\mathrm{error}} - \omega_{\mathrm{base}}}{\omega_{\mathrm{base}}} \qquad (2)$$

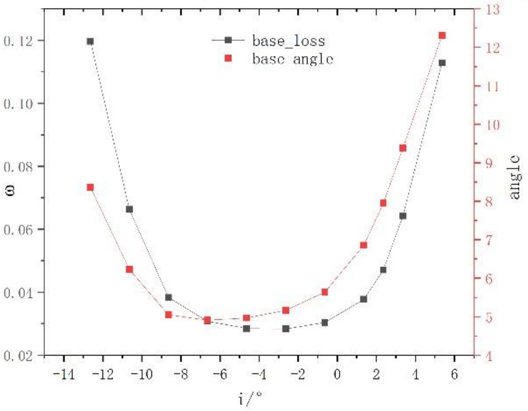
The deviation angle is defined as:

$$angle = angle_{outlet} - angle_{geometry} \qquad (3)$$

The relative outlet deviation angle variation is used to analyze the variation of compressor airfoil deviation angle and is defined as:

$$angle\_Dvalue = angle_{\mathrm{error}} - angle_{\mathrm{base}} \qquad (4)$$

The Inlet Mach number of the compressor airfoil is set as 0.5 during the simulations, and the variation of the compressor airfoil total pressure loss coefficient and deviation angle with the incidence angle is shown in Fig.3. The numerical simulation presented in this study was performed under a fixed Mach number of 0.5Ma. As depicted in Figure 3 the minimum value of the total pressure loss coefficient after the grid is approximately 0.033908, whereas the stability margin of the compressor is from -10 ° to 5° incidence angle when the minimum loss coefficient is taken as twice the range of the stability margin of the compressor. With a change in the incidence angle of the incoming flow, the overall trend is observed to be decreasing initially and then increasing. It is also noteworthy that the deviation angle exhibits its minimum value at an incidence angle of -5°, and as the incidence angle increases, the deviation angle also rises

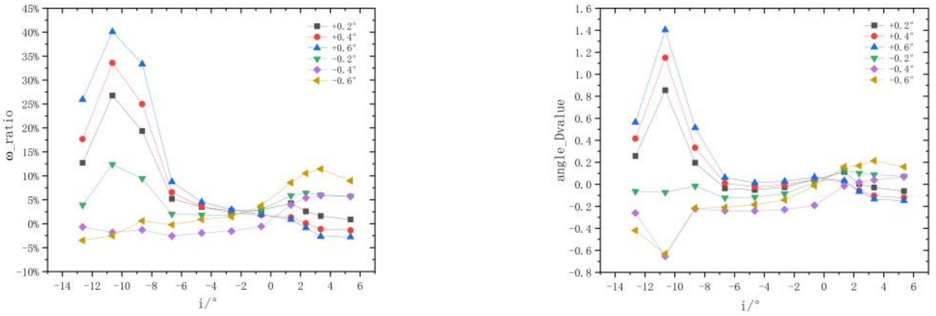


.

FIG. 3 loss coefficient/deviation angle varies with the angle of incidence in the base station

Influence of inlet geometrical angle deviations

The influence of inlet geometrical angle deviations on the aerodynamic performance of compressor airfoil is shown in Fig 4.



(a) Distributions of total pressure loss coefficient

(b) Distributions of deviation angle

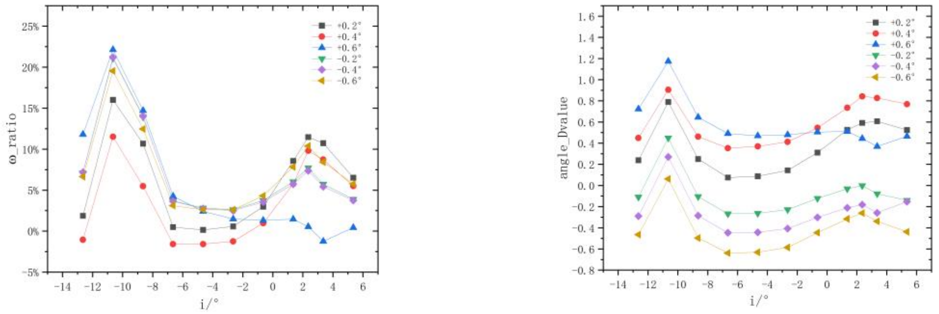
Fig. 4 Influence of inlet geometrical angle deviations on the aerodynamic performance of compressor airfoil

According to Fig 4 (a), for negative incidence angles, the positive inlet geometrical angle deviations will increase the total pressure loss coefficient dramatically. With the incidence angle being -11°, the maximum total pressure loss coefficient increase can be observed with +0.6° inlet geometrical angle deviation, and ωratio reaches 40%. For positive incidence angles, the negative inlet geometrical angle deviations tend to increase the total pressure loss coefficient more, compared with positive inlet geometrical angle deviations. With the incidence angle being +5°, maximum total pressure loss coefficient increase can be observed with -0.6° inlet geometrical angle deviation, and ωratio reaches 10%. It can be found that the aerodynamic performance of compressor airfoil at a negative incidence angle is more sensitive to the inlet geometrical angle deviations, and correspondingly, positive inlet geometrical angle deviation tends to impose a stronger influence on the total pressure loss coefficient of the compressor, compared with negative inlet geometrical angle deviation. It should be noted, the variation of compressor airfoil total pressure loss coefficient associated with both positive and negative inlet geometrical angle deviations is no bigger than 5%. These findings indicate that the influence of inlet geometrical angle deviation on the aerodynamic performance of the compressor at design work conditions is smaller compared with that on the stability margin of the compressor.

According to Fig 4 (b), the influence of the inlet geometrical angle deviations on the compressor airfoil deviation angle at a negative incidence angle is stronger than that at a positive incidence angle, which is similar to the finding in Fig 4 (a). With the incidence angle being -11°, the maximum variation of compressor airfoil deviation angle can be observed. With inlet geometrical angle deviation being +0.6° and -0.6°, the compressor airfoil deviation angle is maximumly increased by 1.4° and decreased by -0.7° respectively. From this perspective, it can be concluded again that the positive inlet geometrical angle deviation tends to impose a stronger influence on the total pressure loss coefficient of the compressor, compared with negative inlet geometrical angle deviation..

Influence of outlet geometrical angle deviations

According to Fig 5(a), for negative incidence angles, the law is a little different from the law shown in Fig 5(a). except for the +0.6°outlet geometrical angle deviations, compared with the positive outlet geometrical angle deviations, the negative one makes more difference in the total pressure loss coefficient. When the incidence angle is -11°, the maximum total pressure loss coefficient increase is caused by the +0.6°outlet geometrical angle deviation, and reached 22.5%, followed by +0.4°outlet geometrical angle deviation which is 22% increase in total loss coefficient. For positive incidence angles, the positive outlet geometrical angle deviation increases more compared with the negative ones. With the incidence angle being +5°, maximum total pressure loss coefficient increase can be observed with +0.2° outlet geometrical angle deviation, and ωratio reaches 5%, against the 2% increase in total pressure loss coefficient caused by +0.6° outlet angle deviation. It can be found that being similar to the law shown in Fig 4, the aerodynamic performance of compressor airfoil at a negative incidence angle is more sensitive to the inlet geometrical angle deviations, simultaneously except the +0.6°outlet geometrical angle deviation, the negative ones tend to exert more influence in ωratio when they compared with the positive ones.



(a) Distributions of total pressure loss coefficient

(b) Distributions of deviation angle.

Fig5. Influence of outlet geometrical angle deviations on the aerodynamic performance of compressor airfoil

According to Fig5(b), the influence of the outlet geometrical angle deviations on the compressor airfoil deviation angle at a positive incidence angle is stronger than that at the negative incidence angle, With the incidence angle being -11°, the maximum variation of compressor airfoil deviation angle can be observed. With inlet geometrical angle deviation being +0.6° and -0.6°, the compressor airfoil deviation angle is maximumly increased by 1.2° and decreased by +0.1° respectively. when the incidence angle being 5°,the maximum deviation angle is +0.7° in +0.4°outlet angle deviation and the minimum is -0.5° in -0.6° outlet angle deviation. From this perspective, it can be concluded again that the positive outlet geometrical angle deviation tends to impose a stronger influence on the total pressure loss coefficient of the compressor, and Under the same geomatic angle deviation, the deviation angle changes gently with the incidence angle, and the variation is the same as the value of geometrical angle deviation in stability margin of the compressor, almost all outlet angle deviation increases the total pressure loss coefficient, which is different from the law when the deviation is in the inlet of the blade. Also, the maximum total pressure loss coefficient fluctuation caused by outlet angle deviation is only half of that caused by inlet angle deviation.

DEVIATION MECHANISM ANALYSIS

Parameter distribution of boundary layer of inlet geometric Angle deviation

Figure 6 shows the program distribution of the leading edge velocity under different incidence angles. For the reference blade profile, we can clearly see the micro-flow separation in the boundary layer at the pressure surface at -8° incidence Angle and the micro-flow separation in the boundary layer at the suction surface at 4°incidence Angle. The flow field at -2° incidence Angle is relatively stable.

When the angle of incidence is -8°, compared with the velocity cloud diagram of inlet geometrical angle deviation under the reference flow field, it is found that +0.6° inlet angle deviation has obvious flow separation and thickening phenomenon on the pressure surface side compared with the reference blade profile. On the contrary, at -0.6°inlet angle deviation, flow separation on the pressure surface side is weakened, indicating that the existence of inlet geometrical angle deviation will change the boundary layer of the pressure surface which means the larger the inlet geometric angle deviation is, the more loss coefficient caused by micro-flow separation will be, leading to a larger total pressure loss coefficient. The velocity cloud of the suction surface can confirm that the inlet angle deviation can also enhance flow separation, but the boundary layer of the suction surface gets a slight influence.

With the incidence angle being -2°, as the increase of inlet angle deviation from negative to positive, the acceleration zone is put forward and starts earlier and earlier, which also enlarges the zone in the suction surface of the blade. Contrary, compared with the reference blade profile, it reduces the acceleration zone in -0.6°inlet angle deviation, while in this incidence angle, geometrical angle deviation has a slight influence on the boundary layer of the suction surface

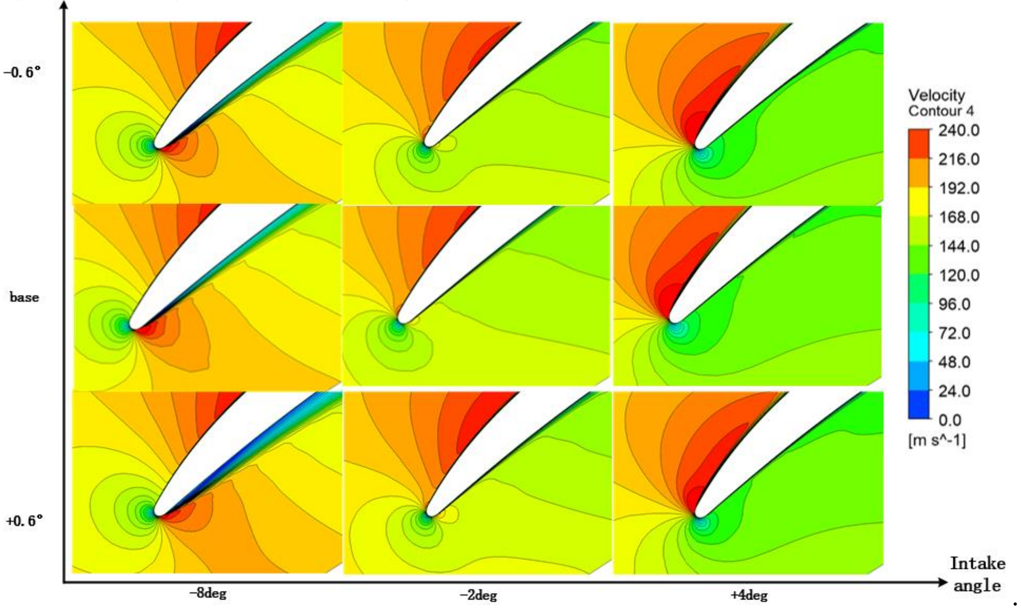


Fig 6 Velocity distribution cloud picture of different incidence angles with different inlet geometric angle deviation

With the incidence angle being 4°, together with the inlet geometrical angle deviation being +0.6°, we can see that compared with the reference blade profile, the boundary layer of the pressure surface gets a slight influence; while in the boundary layer of the suction surface, the acceleration zone is put forward and enlarged, which is similar with the law in incidence angle -2°., On the contrary in a Comprehensive analysis of Fig 7(Liu et al., 2017), the acceleration zone end earlier with the maximum velocity in -0.6°inlet angle deviation which enhances adverse pressure gradient and then stat the micro-flow separation in the boundary.

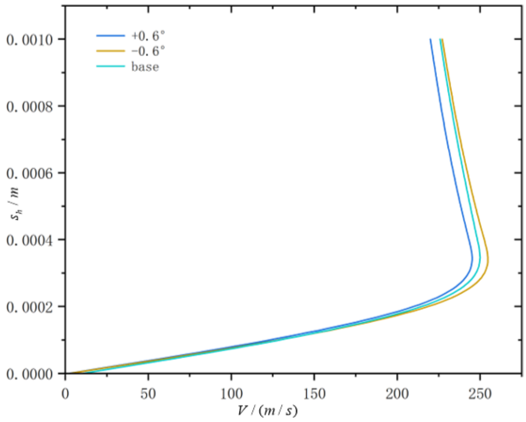
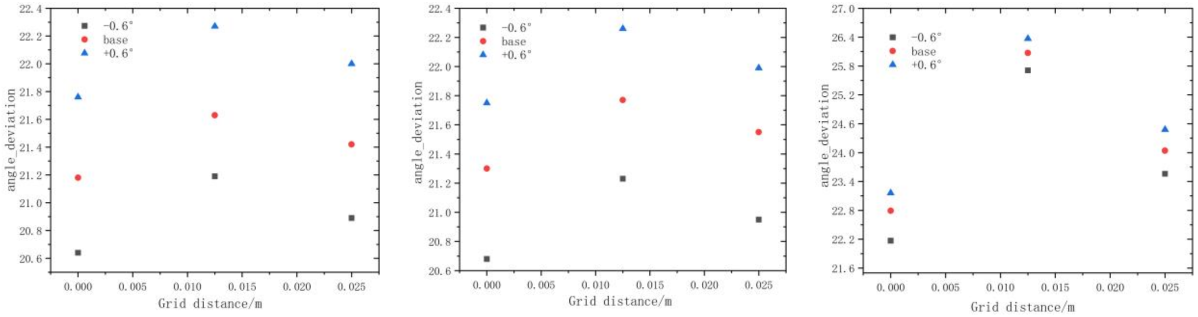


FIG. 7 Velocity pattern distribution in +4° incidence angle

Parameter distribution of boundary layer of outlet geometric Angle deviation

By comparing the impact of inlet geometry angle deviation on compressor aerodynamic performance, our study initially analyzed the velocity distribution diagram of the cascade plane, especially the difference in outlet geometry angle. However, we found that the flow field distribution at the trailing edge was chaotic due to the existence of mixing phenomena, and it was not possible to observe the effect of outlet geometry angle deviation on local flow separation. The influence of FIG.8 represents the 30% axial chord away from the trailing edge of the blade, along with the velocity distributions at three positions on the suction surface side, trailing edge side, and pressure surface side. In FIG. 8, we found that under three intake incidence angles (-8°, -2°, +4°), the deviation amount and error amount of the geometrical angle were essentially the same when compared to the velocity angle of the measurement position of the angle of the foundation blade, and the difference value fluctuated within ±0.1°. Consequently, we concluded that the primary effect of outlet geometrical angle deviation on compressor aerodynamic performance is mainly through changes in the flow direction caused by geometric variations.



(a)-8deg (b)-2deg (c)+4deg

Figure 8 Outlet flow Angle in 30% chord length in different incidence angle

CONCLUSION

Through numerical simulation, this paper investigates the influence of different inlet and outlet geometric angle error deviations on blade aerodynamic performance. The main findings are as follows:

1) Inlet geometric angle deviation significantly impact the total pressure loss coefficient and deviation angles, especially in the negative angle of incidence direction. Larger deviations have a greater impact on aerodynamic performance, but there is also a threshold value where errors can improve blade performance to some extent. A positive angle of incidence is less affected by deviation and has better characteristics.

2) Outlet geometric angle deviation mainly affect the deviation angle, with a small impact on the loss coefficient within a certain range of angles of incidence. And outlet deviation increases the loss coefficient under all angles of incidence.

3) In terms of mechanism, inlet geometric angle deviation affect the development process of the boundary layer and change the position that starts to decelerate and the size of the acceleration zone It also affects peak velocity and then enhances adverse pressure gradient which greatly changes the aerodynamic performance of the compressor

4) Outlet geometric angle deviation affects the direction of airflow development at the trailing edge, which in turn affects the trailing angle distribution.

Overall, this study highlights the importance of geometric angle accuracy in blade design and provides insights into the mechanisms underlying the effects of errors on blade performance.

NOMENCLATURE

C_{ax} = Axial chord length
σ = inlet/outlet geometric angle deviation
β_1 = inlet geometric angle
β_2 = outlet geometric angle
β^1 = deviated inlet geometric angle
β^2 = deviated outlet geometric angle
P_{t1} = the total pressure of the inlet flow
P_{t2} = the total pressure of the outlet flow
P_1 = the static pressure of the inlet flow
ω_{error} = the total pressure loss coefficient of compressor airfoil with angle deviations.
ω_{base} = the total pressure loss coefficient of compressor airfoil in the base blade profile
ω_ratio = Relative value of total pressure loss coefficient
$angle$ = deviation angle of the base blade profile
$angle_{outlet}$ = the outlet flow angle with the base blade profile
$angle_{geometry}$ = outlet geometry angle
$angle\_Dvalue$ = devalue of deviation angle
$angle_{\mathrm{error}}$ = the outlet flow angle of the compressor airfoil with the base blade profile
$angle_{\mathrm{base}}$ = the outlet flow angle of the compressor airfoil without the angle deviations

S_h = the velocity profile

REFERENCE

Cumpsty, N.A. (1989). Compressor aerodynamics. The Open Library. Harlow, Essex, England, New York: Longman Scientific & Technical.

Tubbs, H. (1991) “Compressor Aerodynamics. By N. A. CUMPSTY. Longman, 1989. 509 pp. £49.,” Journal of Fluid Mechanics. Cambridge University Press, 226, pp. 659–659.

Suder, K.L., Chima, R.V., Strazisar, A.J. and Roberts, W.B. (1995). The Effect of Adding Roughness and Thickness to a Transonic Axial Compressor Rotor. Journal of turbomachinery, 117(4), pp.491–505.

Walraevens, R.E. and Cumpsty, N.A. (1995). Leading Edge Separation Bubbles on Turbomachine Blades. Journal of Turbomachinery, 117(1), pp.115–125.

Lu and Xu (2000). improvement of compressor blade leading edge design. Journal of Aerospace Power, 15(2), p.4.

Liu, Li, and Jiang (2002). Effect of Leading Edge Geometry on Separation Bubble on NACA65 Compressor. Journal of Engineering Thermophysics, 24(2), pp.231–223.

Xu, L. (2003). Circular Leading Edge With a Flat for Compressor Blades. Journal of Propulsion Technology, 24(6), p.5.

Liu, Jiang, and Chen (2004). An Experimental Investigation of The Flow on Leading Edge of Compressor Blade. Journal of Engineering Thermophysics, 25(06), pp.936–939.

Ballal, D.R. and Zelina, J. (2004). Progress in Aeroengine Technology (1939--2003). Journal of Aircraft, 41(1), pp.43–50.

Wheeler, A.P.S., Sofia, A. and Miller, R.J. (2009). The Effect of Leading-Edge Geometry on Wake Interactions in Compressors. Journal of Turbomachinery, 131(4).

Goodhand, M.N. and Miller, R.F. (2011). The Impact of Real Geometries on Three-Dimensional Separations in Compressors. Journal of turbomachinery, 134(2).

Liu, Yuan and Yu (2013). Effect of Leading Edge Geometry on Aerodynamic Performance in Controlled Diffusion Airfoil. Journal of Propulsion Technology, 34(7), p.8.

Song and Gu (2013a). Continuous Curvature Leading Edge of Compressor Blading. Journal of Propulsion Technology, 34(11), p.8.

Song and Gu (2013b). Effect of Leading Edge on the Aerodynamic Performance of Compressor. Journal of Engineering Thermophysics, 34(6), p.4.

Liu, B.J., Yuan, C.X. and Yu, X. (2017) Effects of leading-edge geometry on aerodynamic performance in controlled diffusion airfoil. Journal of Engineering Thermophysics,38(10).