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Criteria for designing low-loss and wide operation range variable inlet guide vanes

Hengtao Shi[a], Baojie Liu[a,b,c], Xianjun Yu[a,b,c,*]

[a] School of Energy and Power Engineering, Beihang University, No. 37, Xueyuan Road, Haidian District, Beijing 100191, China
[b] National Key Laboratory of Science & Technology on Aero-Engine Aero-Thermodynamics, Beihang University, China
[c] Collaborative Innovation Center of Advanced Aero-Engine, Beihang University, China

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ABSTRACT

Critical factors influencing the variable inlet guide vane (VIGV) profile loss at high incidence condition were studied by using numerical methods and a practical design criterion for designing wide low-loss operation range VIGVs in axial-flow compressor was proposed. At first, to acquire research samples, a series of airfoils with different shapes were generated for two selected representative VIGV cascade cases. Steady simulations based on Reynolds-Averaged Navier–Stokes method, carried out by commercial software CFX and validated with experimental data after grid independent study, were first conducted to predict the aerodynamic performances, the surface velocity distributions and the boundary-layer behaviors of the generated airfoils. Based on the simulated results, the influences of geometric parameters on airfoil performances were analyzed and the geometric features of low-loss VIGV airfoil were revealed. Further analysis indicated that the magnitude of airfoil loss at high incidence condition were mainly influenced by the scales of two boundary-layer separation regions: one at the leading edge caused by the high adverse pressure gradient induced by the suction spike and the other one caused by the adverse pressure gradient induced by the re-acceleration flow. To reveal the influence of the suction spike and the re-acceleration flow on the scales of separation regions, two practical parameters D_{spike} and A_{re} were defined. It was found that there exists an optimized range of the D_{spike} and A_{re} which could keep the separation flow to a small scale at high incidence condition and can be used as a surface velocity design criterion for designing wide low-loss operation range VIGVs. Moreover, the methods for choosing the airfoil geometric parameters to achieve the preferred surface velocity distribution were discussed. Finally, the developed design criterion was used to guide the airfoil modification of an axial-flow compressor VIGV and achieved an average of 19%, 52% and 73% loss coefficient reduction at three high stagger angle operating points, which confirms the applicability and effectiveness of the design criterion in three-dimensional environment.

1. Introduction

Variable inlet guide vanes (VIGVs) are widely used in axial flow compressors for providing the requested flow angles into the downstream rotor and improving its performance at off-design conditions [1–4]. VIGVs used in axial-flow compressors are usually designed to have a certain camber angle and operate at negative incidence at the design condition [5], which is different from the inlet guide vane with symmetric profile used in centrifugal compressor [6]. At off-design points, as the stagger angle of the vane increases to high incidence, the total pressure loss of VIGV usually increases remarkably [7,8], which can cause considerable reduction of compressor efficiency. At high incidence condition, since the inflow leading edge stagnation point has moved to the pressure side, the flow in VIGV along the suction side experiences a strong acceleration in the vicinity of the leading edge and forms a velocity peak [7,8]. Downstream of the leading edge velocity spike, the subsequent high adverse pressure gradient, induced by the velocity diffusion, causes rapid growth of suction surface boundary-layer and even massive flow separation, which leads to the high total pressure loss and limits the useful operating range [7–9]. Sanz et al. found that the scale of the separation region and the profile loss level increased with the rise of the leading edge velocity peak, moreover, the shape of the former portion of the airfoil and the incidence angle have crucial influences on the height of the velocity peak as well as the profile loss level [9]. The reduction of the

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[*] Corresponding author at: School of Energy and Power Engineering, Beihang University, No. 37, Xueyuan Road, Haidian District, Beijing 100191, China.
E-mail address: yuxj@buaa.edu.cn (X. Yu).

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Nomenclature

c	chord length	mm
i	nominal incidence	degree
k	specific heat ratio, $k = 1.4$	
l_{S1}	leading edge separation length	mm
l_{S2}	re-acceleration induced separation length	mm
p	static pressure	Pa
r	radius measured from axis of rotation	mm
s	tangential spacing	mm
t_{LE}	airfoil leading edge thickness	mm
t_{TE}	airfoil trailing edge thickness	mm
$t_{\max}$	airfoil maximum thickness	mm
u	isentropic surface velocity, $\sqrt{\frac{2k}{k+1}\mathrm{R}T_{\mathrm{t}1}}\sqrt{\frac{k+1}{k-1}[1-(\frac{p}{P_1})^{\frac{k-1}{k}}]}$	m/s
u_1	inflow freestream velocity, $\sqrt{\frac{2k}{k+1}\mathrm{R}T_{\mathrm{t}1}}\sqrt{\frac{k+1}{k-1}[1-(\frac{p_1}{P_1})^{\frac{k-1}{k}}]}$	m/s
u_e	main flow velocity at edge of boundary-layer	m/s
$u_{\min}$	surface velocity at trough point	m/s
$u_{\max 1}$	surface velocity at suction spike peak	m/s
$u_{\max 2}$	surface velocity at re-acceleration flow peak	m/s
x	coordinates in chord-wise direction	mm
$x_{\mathrm{LES.\,inp.}}$	normalized chord location of incipience point of leading edge suction spike induced separation	
$x_{\mathrm{LES.\,ret.}}$	normalized chord location of reattachment point of leading edge suction spike induced separation	
$x_{\mathrm{RAS.\,inp.}}$	normalized chord location of incipience point of re-acceleration flow induced separation	
$x_{\mathrm{RAS.\,ret.}}$	normalized chord location of reattachment point of re-acceleration induced separation	
y	coordinates perpendicular to chord-wise direction	mm
A_{re}	re-acceleration strength factor, $A_{\mathrm{re}} = 1 - u_{\min}/u_{\max 2}$	
$AVDR$	axial-velocity-density-ratio	
C_f	surface friction coefficient, $C_f = \mu(\partial u/\partial y)_{\mathrm{wall}}/(0.5\rho U^2)_{\text{main flow}}$	
C_L	mean-line lift coefficient	
C_{m}	mean-line maximum deflection location	
C_p	airfoil surface pressure coefficient, $C_p = (p - p_1)/(P_1 - p_1)$	
D_{spike}	spike diffusion factor, $D_{\mathrm{spike}} = 1 - u_{\min}/u_{\max 1}$	
H_b	boundary-layer shape factor, $H_b = \delta_1/\delta_2$	
L	aerodynamic chord length	mm
LE	leading edge	
Ma	Mach number	
P	total pressure	Pa
P_{m}	airfoil maximum thickness location	
R_{g}	specific gas constant for air, $R_{\mathrm{g}} = 287.06\mathrm{J}/(\mathrm{kg}\cdot\mathrm{K})$	
R	blade span, $\mathrm{R} = (r - r_{hub})/(r_{tip} - r_{hub})$	
Re_1	Reynolds number based on airfoil chord-length and inlet flow property, $Re_1 = (v_1 \cdot L)/\nu_1$	
T	airfoil maximum relative thickness	
TE	trailing edge	
T_{t}	total temperature	K
Tu	turbulence intensity, $Tu = \sqrt{(u_{1x}'^2 + u_{1y}'^2 + u_{1z}'^2)}/\lvert u_1\rvert$	
β	flow angle measured from axial direction	degree
$\Delta\beta_2$	variation of exit flow angle, $\Delta\beta_2 = \beta_2 - \beta_{2D}$	degree
$\Delta\beta_{\mathrm{PR}}$	low-loss operation range toward high stagger angle	degree
$\Delta\beta_{\mathrm{NR}}$	low-loss operation range toward low stagger angle	degree
γ	VIGV blade stagger angle	degree
$\Delta\gamma$	variation of VIGV blade stagger angle with respect to the design condition	degree
δ_{LES}	airfoil leading edge wedge angle	degree
δ_1	boundary-layer displacement thickness	mm
$\delta_{2\mathrm{S}}$	suction surface boundary-layer momentum thickness	mm
θ	camber angle	degree
σ	blade passage averaged total pressure recovery coefficient, $\sigma = \overline{P}_2/P_1$	
χ	suction surface local incidence, $\chi = i - \delta_{\mathrm{LES}}$	degree
ω	cascade passage averaged total pressure loss coefficient, $\omega = (P_1 - \overline{P}_2)/(P_1 - p_1)$	
Λ_{R}	pressure gradient parameter at boundary-layer edge, $\Lambda_{\mathrm{R}} = \frac{\theta}{u_e}\frac{du_e}{dx}$	

Subscripts

1	inlet location
2	outlet location
30	value at operation point with $\Delta\beta_2$ equaling to 30 degrees
ax	axial direction
D	value at design point
REF	reference value

total pressure recovery coefficient of a typical VIGV can reach or exceed 1.0 percentage point once the setting angle increase 25 degrees relative to the design condition [10], which can cause a 0.5 percentage point or higher reduction of adiabatic efficiency for a moderate pressure ratio compressor. Moreover, the wake losses of a guide vane can be further enlarged by the downstream transonic rotor, compared with the steady state, due to the passing shock interaction on the guide vane in some cases [11]. Since the shape of airfoil is a key factor to affect the VIGV performance by influencing the flow field and the boundary-layer development [9], developing a practical method for optimizing the VIGV airfoil could be a convenient and effective way to improve the performance of VIGV.

For designing of VIGVs, several kinds of airfoil have been used, including the NACA65 series [12,13], the C4 series [14], the NACA63-A4K6 series [5,15,16] and the control diffusion airfoils [17]. The NACA65 series and C4 series are typical airfoils in subsonic compressors and the extensive experimental data make it convenient to provide fast design for VIGVs [12–14]. In 1957, Dunavant presented an effective vane profile of NACA63-A4K6 series [7], which was designed to operate at high subsonic inflow Mach number for extending the choking limit due to the demand of high through-flow compressors. From the late of 1970s, based on some experimental and numerical researches, controlled diffusion airfoils (CDA) were gradually introduced into modern compressor design and also selected as the blade element in some recent VIGVs [17]. Among these profiles, the NACA63-A4K6 profiles are more widely-used for designing the compressor guide vanes including the VIGVs of the well-known Energy Efficient Engine (E^3) core compressor [5], the LM2500+ compressor [16] and proved to provide reliable performance.

As an important component of axial-flow compressors, the loss level of VIGVs has considerable influence on the compressor efficiency as mentioned previously. Due to the demand of improving the compressor efficiency, it is necessary to systematically reveal how the airfoil shape and flow phenomena influence the loss-level of VIGVs in axial-flow compressor, and consequently, to de-