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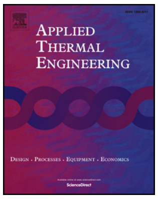

Research Paper

Combined application of negative bowed blades and unsteady pulsed holed suction in a high-load compressor in terms of aerodynamic performance and energy efficiency

Hongxin Zhang, Shaowen Chen*, Yun Gong, Songtao Wang, Zhongqi Wang

School of Energy Science and Engineering, Harbin Institute of Technology, Harbin, Heilongjiang 150001, China

HIGHLIGHTS

- Energy efficiency is introduced.
- Compound flow control (CFC) technique is proposed.
- Studies the effects of CFC at different negative bowed angles.
- Studies the effect of excitation parameters on aerodynamic performance and energy efficiency.

ARTICLE INFO

Keywords:
Energy efficiency
Endwall unsteady pulsed holed suction
Compound flow control
Highly loaded compressor cascade
Excitation parameters

ABSTRACT

Active flow control techniques applied to compressors have been known to bring benefits at the cost of additional energy consumption. The viability of suction as a major active flow control technique, however, has been rarely estimated. In this study, energy efficiency was chosen as a parameter for the evaluation of the benefit relative to the cost of suction. The particular suction technique under investigation was endwall unsteady pulsed holed suction (EUPHS) which was combined with negative bowed blades as a novel application of the compound flow control (CFC) approach in order to obtain improved aerodynamic performance. The results showed the EUPHS was more effective in reducing time-averaged total pressure losses than the endwall steady constant holed suction (ESCHS) with the same suction-to-inlet time-averaged suction flow ratio m_s. The advantage of a higher energy efficiency achieved by the EUPHS over the ESCHS, however, would correspondingly decline when m_s was increased. The CFC presented a more obvious positive effect when compared with the ESCHS combined with negative bowed blades (CFC-steady) at different negative bowed angles and excitation locations, with the optimal negative bowed angle at $\Phi = 10^\circ$ for CFC and CFC-steady. With the ensuing optimization of the CFC ($\Phi = 10^\circ$), the total pressure loss coefficients were reduced by 18%. A highest energy efficiency for CFC ($\Phi = 10^\circ$) was achieved at a relatively lower $m_s = 0.4\%$, and the time-averaged energy efficiency reached as high as 504%. The potentials of CFC ($\Phi = 10^\circ$) at different incidence angles were also validated.

1. Introduction

Energy demand of modern gas turbine engines is increasing with the rapid development of industry. In order to obtain more benefits with less energy consumption, it is necessary to apply some effective techniques [1–7].

In the recent years, the investigation of unsteady active flow control (UAFC) technique is drawing more attention since UAFC technique is considered more effective and efficient than the conventional steady active flow control (SAFC) technique [8,9]. Unsteady blowing was proved to be superior in its performance by Cetin et al. [10], who investigated experimentally the effects of steady and unsteady blowing on the flow structure over a nonslender delta wing. Pulsed VGJs was found to be better than steady vortex generator jets (VGJs) in controlling flow separations at a fixed mass flow rate [11]. The applications of UAFC technique to turbomachinery blading were investigated by many researchers who recognized the promising results of UAFC technique in external flows. Evans et al. [12] found by that pulsed jet had an obvious superiority to steady jet in suppressing flow separations on the surface of a flat plate equaling on the suction side of the compressor. The

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* Corresponding author.
E-mail address: cswemail@hit.edu.cn (S. Chen).

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Nomenclature

UAFC	unsteady active flow control
SAFC	steady active flow control
SCS	steady constant suction
ESCHS	endwall steady constant holed suction
EUPHS	endwall unsteady pulsed holed suction
CFC	compound flow control
CFC-steady	ESCHS combined with negative bowed blade
SST	shear stress transport
EXP	experimental
CFD	computational fluid dynamics
FFT	Fast Fourier Transformation
Unexcited	baseline case
average	time-averaged
PS	pressure side
SS	suction side
N	mesh number
α	pitch angle
β	skew angle
i	incident angle
Φ	negative bowed angle
f	excitation frequency
f_{shed}	natural frequency of vortex shedding
f_e	relative excitation frequency
t	simulation time
T	one excitation cycle
ρ	density
b	chord length
l	axial chord length
e	pitch
$\bar{h}\overset{?}{\mathrm{h}}$	spanwise normalized
h_b	bowed length
A_F	exit area of the bleeding hole
γ	stagger angle
θ_1	inflow angle
θ_2	outflow angle
$\Delta\theta$	CAMBER angle
U_{max}	Maximum suction velocity
m_s	suction-to-inlet time-averaged suction flow ratio
ϖ	time-averaged total pressure loss coefficient
$\Delta\varpi$	relative time-averaged total pressure loss coefficient
Cp	static pressure coefficient
η_{Energy}	time-averaged energy efficiency
$\overline{W_G}$	time-averaged energy gain of the suction
$\overline{W_F}$	time-averaged energy consumption of the suction
p	Static pressure
p^*	total pressure
Ω	vorticity tensor
S	shear strain rate tensor
y+	dimensionless wall distance

Subscripts

in	inlet of the computational domain
out	outlet of the computational domain
*	total condition

comparison between steady and unsteady plasma excitation for controlling flow separations showed that the unsteady plasma excitation had advantages over steady one such as better aerodynamic performance and less power consumption [13]. The effectiveness of steady blowing and pulsed blowing in delaying or even eliminating separation in a critically loaded compressor cascade is explored by Hecklau et al. [14–16], who found that pulsed blowing could better control flow separations. It might be suggested that the above-mentioned UAFC techniques were more efficient than the steady active flow control (SAFC) techniques in boosting the aerodynamic performances possibly due to their difference in the conditions for their applications. For the conventional SAFC technique, the imposed effects on flow fields in the passage of the compressor were generally constant over time. By contrast, the current UAFC technique could introduce some unsteady controlling parameters and factors to consider the influence of unsteady characteristics on flow control strategies in the design of the compressor.

The excitation frequency, amplitude and location are important parameters and factors of the UAFC technique, which are gaining attention because they play significant roles in determining compressor performances. Braunscheidel et al. [17] applied unsteady synthetic jet in a low-speed axial compressor and revealed that the improvement of aerodynamic performance was related to the excitation amplitude, but the excitation frequency had limited influence on control effect. In the work of Cerretelli [18], the flow was fully reattached and the maximum pressure recovery was achieved only at a suitable excitation frequency. In addition, unsteady excitation was shown to have a significant effect in enhancing the performance of the axial compressor and decreasing the loss coefficient when the excitation frequency, amplitude and location were in their optimum ranges [19,20].

Steady constant suction (SCS) as a SAFC has been applied extensively to suppress flow separations since it was first introduced by Kerrebrock et al. to boost aerodynamic loading and efficiency in the design of the compressor [21,22]. Nevertheless, there have been only a few published reports related to the influences of unsteady aspiration on the aerodynamic performance of a fluid machine. Arakeri et al. [23] explored the relationship between unconditioned pulsed slot suction control and the turbulent boundary layer and found that a higher frequency and temporal selection of control positions are important to the improvement of the flow structure. In the research of Hassan [24], a pulsed suction jet had beneficial effects on the separated boundary layer flow over the airfoil.

However, for a compressor using a conventional SCS, a large suction flow [25] would increase energy consumption of the compressor, and suction slots [26] and multi-bleeding holes [27] on the suction surface of compressor blades, particularly a thin compressor blade, would also reduce the blade strength to some extent.

To avoid these disadvantages of SCS, therefore, it is imperative to develop a better suction strategy with less suction flow and fewer suction slots/holes than the conventional SCS in the design of the compressor. In view of the above-mentioned facts, a technique named as endwall unsteady pulsed holed suction (EUPHS) was first developed. Two bleeding holes symmetrically mounted on the endwalls (one on the upper endwall and the other on the lower endwall) were used to achieve the suction in a highly loaded compressor cascade and the suction-to-inlet time-averaged suction flow ratio was expected to be much less than that of the conventional SCS.

Table 1
Geometrial parameters of the cascade.

Parameters	Value
Chord b/mm	100
Solidity b/e	1.25
Aspect ratio h/b	1
Stagger angle $\gamma/^\circ$	18.4
Inflow angle $\theta_1/^\circ$	48.185
Outflow angle $\theta_2/^\circ$	−11.815
Camber angle $\Delta\theta/^\circ$	60