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# Flow separation control using unsteady pulsed suction through endwall bleeding holes in a highly loaded compressor cascade

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Unsteady pulsed suction (UPS) as a novel unsteady flow control (UFC) technique is applied in a certain highly loaded compressor cascade for the control of flow separations. Some related aerodynamic parameters such as excitation frequency and time-averaged suction flow rate are studied in detail. UPS and steady constant suction (SCS) are investigated to analysis comparatively the control effects of flow separations with the same time-averaged suction flow rate. The results show that UPS can provide appreciable improvement of cascade performance in a wide range of excitation frequencies. There are different optimum frequencies under different time-averaged suction flow rates, but the optimum frequencies are both an integer multiple of the natural frequency of vortex shedding. Based on the optimum frequency, the total pressure loss coefficients under the time-averaged suction flow rates $m_s = 0.4\%$ and $m_s = 0.53\%$ are reduced by 9.4% and 14.2%, respectively. The time-averaged suction flow rate plays a more crucial role than the excitation frequency. Simultaneously, UPS can provide a better flow control effect than SCS with the same time-averaged suction flow rate in the control of flow separation. The time-averaged suction flow rate range that can obtain positive effects for UPS is wider than that for SCS. Additionally, the potentials of UPS at off-design points are also validated.



## 1. Introduction

In modern compressor designs, the continually increasing blade load results in three-dimensional (3D) unsteady flow separation and a decrease in aerodynamic efficiency. With the purpose of improving the aerodynamic performance of axial compressors, therefore, it is necessary to adopt some positive techniques to control the 3D flow separation. The investigation of flow separation control has attracted great interest among many researchers and is gradually becoming a hot research topic [1–6]. Especially in the last several years, the UFC technique as a new potential method has been considered to provide more effective and sophisticated control in flow separation than the traditional steady flow control (SFC) technique [7,8]. The new trends are attracting a lot of attention and a further improvement of flow is expected by developing the UFC technique.

For the traditional SFC technique, the imposed effects on flow fields in the passage of the compressor are generally constant over time and it is difficult to consider the influence of unsteady characteristics on flow control strategies in the design of the compressor. However, the current UFC technique can achieve a better flow control effect by the introduction of unsteady controlling parameters and factors in the control of flow separation. Schatz and Thiele [7] delayed the flow separations in a two-element high-lift configuration by periodic excitation and it was found that oscillatory suction and blowing is about 10 times more effective in terms of lift than steady blowing. Seifert et al. [8] investigated the effect of oscillating jets as a way of delaying separation around a NACA 0015 airfoil and the research results showed that the injected mass flow decreases by one order of magnitude when using oscillating jets rather than steady ones. And the studies by Wygnanski [9] showed that periodic suction and blowing has a marked superiority in delaying or even eliminating separation compared with steady blowing. Apart from these researches about external flow, the UFC technique also has a wide range of application in the research field of internal flow. De Giorgi et al. [10–12] controlled flow separations on a highly-loaded low-speed compressor cascade by adopting different flow control methods, and they found that the unsteady synthetic jet has greater advantages than the steady jet in saving energy consumption and reducing total pressure losses. Vortex generator jets were also applied to alleviate flow separations on the surface of a flat plate equaling on the suction side of the compressor [13]. The results showed that steady blowing can successfully suppress separation and decrease

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**Nomenclature**

| | |
|---|---|
| UPS | Unsteady pulsed suction |
| UFC | Unsteady flow control |
| SCS | Steady constant suction |
| SFC | Steady flow control |
| EXP | Experimental |
| FFT | Fast Fourier Transformation |
| Ori | Baseline case |
| LE | Leading edge |
| TE | Trailing edge |
| SL | Separation line |
| $N$ | Mesh number |
| $H$ | Shape factor |
| $\delta^*$ | Displacement thickness |
| $\theta$ | Momentum thickness |
| $h$ | Blade height |
| $\alpha$ | Pitch angle |
| $\beta$ | Skew angle |
| $f$ | Excitation frequency |
| $f_{\text{shed}}$ | Natural frequency of vortex shedding |
| $f_e$ | Relative excitation frequency |
| $t$ | Simulation time |
| $U_m$ | Maximum suction velocity |
| $C_p$ | Static pressure coefficient |
| $C_f$ | Skin friction coefficient |
| $m_s$ | Time-averaged suction flow rate |
| $\varpi$ | Time-averaged total pressure loss coefficient |
| $\rho$ | Density |
| $u$ | The local velocity component paralleling to the blade surface |
| $p$ | Static pressure |
| $p^*$ | Total pressure |
| $y^+$ | Dimensionless wall distance |

*Subscripts*

| | |
|---|---|
| in | Inlet of the computational domain |
| out | Outlet of the computational domain |
| suction | Outlet of the bleeding hole |
| $s$ | Free stream of the edge of the boundary layer |
| $*$ | Total condition |

the loss coefficient. However, when using pulsed blowing, the same effects could be achieved with the injected mass flow rate of 60%. The experimental and numerical results of Hecklau et al. [14–16] confirmed that it is the benefit of pulsed blowing in improving the cascade performance that is more obvious, and the jet mass flow of pulsed blowing is less than that of steady blowing on the suction surface and sidewalls of a critically loaded compressor cascade. Therefore the potential UFC techniques mentioned above are actually proven to provide a greater improvement of cascade performance than the SFC technique.

Moreover, the excitation frequency and amplitude that play a significant role in the UFC technique are gaining increasing attention in order to further explore the superiority of the UFC technique. Volino [17] applied a synthetic vortex generator jet on the suction surface of a low-pressure turbine airfoil and investigated the effect of jet frequency and amplitude on flow separations. The dimensionless pulsing frequency F+ of order 1 was studied as one of the key unsteady controlling parameters, where F+ was defined as the ratio of excitation frequency against the frequency of flow through the chord length. A suitable excitation frequency F+ should be chosen to reduce flow unsteadiness on the body and in its wake [18]. In addition, unsteady flow separations could be controlled effectively by unsteady excitation when the excitation frequency was precisely equivalent to the characteristic frequency of vortex shedding, and the improvement was distinct only if the excitation amplitude was in an optimum range [19,20]. Li et al. [21] investigated the control effects of steady and pulsed jets in bowed compressor cascades and found that the loss decreased more obviously with the increase of excitation amplitude and frequency.

Steady constant suction (SCS) as an effective SFC method was first applied by Kerrebrock et al. in compressor design to boost aerodynamic loading and decrease losses [22,23]. SCS by slots or holes was always used for controlling flow separations [3,24–27]. Up to now, little of the published research has focused on the effects of unsteady aspiration on the aerodynamic performance of a fluid machine. Arakeri and Narasimha [28] studied the effects of unconditioned pulsed slot suction control on the turbulent boundary layer and believed that a higher frequency, or more favorable spatial and/or temporal selection of control positions, is essential for improving the flow structure. Hassan's research [29] also proved that a pulsed suction jet could partially reattach the separated boundary layer flow over the airfoil. In addition, for a compressor using a traditional SCS, a large suction flow [27] in the compressor could cause increased energy consumption, and suction slots [25] and multi-bleeding holes [26] on the suction surface of the compressor blade, particularly for a thin compressor blade, could also decrease the blade strength to some extent. To avoid these disadvantages of SCS, therefore, it is essential to develop a better suction strategy with less suction flow and fewer suction slots/holes than the traditional SCS in the design of the compressor.

So far, related research focused on UPS in an axial compressor cascade has not been seen in the published works. In this study, UPS as a novel UFC technique was applied in a certain highly loaded compressor cascade to control the flow separations. It is expected to hold greater promise for improving the aerodynamic performance of compressor than the traditional SCS. Only two bleeding holes on the endwalls (one on the upper endwall and one on the lower endwall) were set up to achieve the UPS and the total suction flow rate was expected to be much less than that for traditional SCS. A more exciting effect of controlling the flow separation and decreasing the aerodynamic performance was obtained compared to SCS with the same time-averaged suction flow rate and the related aerodynamic parameters and flow fields were discussed and analyzed in detail. Finally, the control effects of UPS under off-design points were also studied. The objective of this study is to investigate the fundamental controlling mechanism using UPS in different suction strategies with different excitation frequencies and different time-averaged suction flow rates for improving the aerodynamic performance and flow separation, especially for the spatial-temporal oscillation of the flow parameters and flow fields.

## 2. Numerical model and methods

### 2.1. Numerical model

A highly loaded compressor cascade of NACA65 profile with a 60° camber angle was used in this study. More details of the cascade are given in Table 1. The schematic diagram of the blade profile and two bleeding holes symmetrically mounted on the endwalls (one on the upper endwall and one on the lower endwall) is