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

GPPS-TC-2023-0103

# INTERACTION MECHANISM BETWEEN INCOMING VORTEX AND TIP LEAKAGE VORTEX BREAKDOWN OF A COMPRESSOR CASCADE

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## ABSTRACT

Steady and unsteady simulation are utilized to investigate the interaction mechanism between casing incoming vortex and tip leakage vortex breakdown (TLVB). The incoming vortex is introduced by using vortex generator. Pitchwise location effect and rotating effect are firstly investigated at steady condition; then, unsteady investigation is employed based on the steady results. At steady condition, the TLVB can be completely removed by incoming vortex with stagger angle of 72° and pitchwise location of y3 (the pitchwise distance between blade leading edge and trailing edge of vortex generator is a half of pitch). The flow mechanism is that the vortex core of TLV is replaced by incoming vortex, which has higher strength, and the ability of TLV to withstand adverse pressure gradient is increased. Moreover, tip leakage mass flow near leading edge is also increased because of the increase of blade loading, coupled with the moderate adverse pressure gradient, the reduction of TLVB is achieved. The unsteady fluctuation on blade passage mainly caused by the interaction between incoming vortex and TLV near leading edge. The distribution of pressure near blade surface is also periodical disturbed by incoming vortex, and the fluctuation of pressure is mainly induced by incoming vortex.

**Keywords:** Tip leakage vortex, Incoming vortex, Vortex breakdown, Compressor cascade

## INTRODUCTION

The tip leakage flow, passing through blade tip due to the pressure gradient from pressure surface to suction surface, is an inherent flow character for compressors [1]. As a result of the interaction between tip leakage flow and mainstream, a vortex which called 'tip leakage vortex (TLV)' is formed, and plays a significant role on the loss, performance and stability of compressors [2-4].

The flow structure and loss mechanism of TLV has been widely numerical and experimentally investigated [5-6]. It is well known that TLV in compressor is highly unsteady, and tip leakage vortex breakdown (TLVB) is one of the flow characteristics [7]. Vortex breakdown is first found and investigated in external flow, whose appearance is concerned with adverse pressure gradient in the streamwise direction and the swirl intensity of the TLV [8]. In 1998, Furukawa et al. [9] found the TLVB in compressor rotors, which changed vortex nature and behavior of TLV. Since then, numerous investigations focus on the flow mechanism of TLVB and its effect on performance of compressors [10-11].

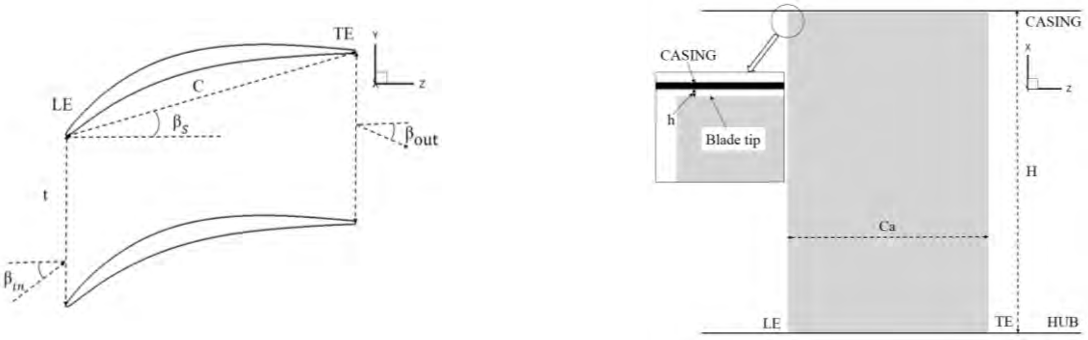
The investigations about TLVB are mainly using steady inlet flow condition. However, due to the effect of interactions between rows in compressors, the inlet surface and flow inside blade passage are highly unsteady [12-13]. Soranna et al. [12] and Wheeler et al. [13] investigated the effect of incoming wake of inlet guide vane on the flow field of compressor, illustrating that interaction between incoming wake and leading edge exerted an important effect on flow field inside blade passage. Periodical unsteady flow in compressors due to the wake-tip clearance vortex interaction was provided by Mailach et al. [14], showing that tip leakage vortex was divided into several parts because of the periodical effect of stator wake. There are plentiful investigations focus on the effect of incoming wake on the flow field on compressor. However, it can be noticed that the existence of stator wake is dominated by vortex structures such as passage vortex etc. near endwall [14].

Hence, the incoming flow for rotor at downstream of stator is always vortical. Nevertheless, few investigations pay attention to the effect of vortical incoming flow on the effect of flow field, especially on tip leakage flow. Ma et al. [15-17] proposed several investigations on the interaction between incoming vortex and tip leakage flow, the gap effects, periodic and aperiodic unsteady effect of incoming vortex on TLV were investigated.

It can be concluded above that incoming flow for a rotor is periodically affected by vortical flow from the upstream stator. The effect of incoming vortical flow on TLV is also investigated. As an important flow character of TLV, TLVB is also affected by vortical incoming flow and the interaction flow mechanism is crucial for compressors. However, there are fewer investigations focus on the effect of vortical incoming flow on TLVB. In this study, interaction mechanism between vortical incoming flow and tip leakage vortex breakdown of a compressor cascade is investigated. In order to provide a vortical incoming flow (incoming vortex), endwall vortex generator is utilized. At steady condition, the pitchwise position effect and rotation direction effect of incoming vortex are investigated. Based on the conclusion of steady condition, unsteady effect of moving incoming vortex on TLVB is also investigated.

## GEOMETRICAL AND AERODYNAMIC PARAMETERS

In order to investigate the interaction mechanism between incoming vortex and tip leakage vortex breakdown, a compressor cascade with tip clearance was selected and numerically simulated. The detailed definition of geometry is showed in Fig. 1, and the key parameters are given in table 1. The tip clearance in this study is 0.5 mm.



(a) Blade to blade plane (b) Meridian plane

Fig. 1. Geometrical definition of baseline compressor cascade

Table 1. Geometrical and aerodynamic parameters

| Parameters | Data |
|---|---|
| Chord (C) / mm | 65 |
| Solidity (C/t) | 1.82 |
| Aspect ratio (H/C) | 1.54 |
| Tip clearance height (h) /mm | 0.5 |
| Stagger angle ($\beta_S$) / ° | 15.2 |
| Inlet flow angle ($\beta_{in}$) / ° | 42 |
| Turning angle ($\beta_{in}$-$\beta_{out}$) / ° | 46.6 |
| Inlet flow Mach number ($Ma_1$) | 0.6 |
| Reynolds number (Re) | $8.3\times10^5$ |

## NUMERICAL METHOD AND VALIDATION

On the basis of the periodical flow field, the computational domain consists of a single blade passage. The inlet boundary of the computational domain is located at -150% axial chord, while the outlet boundary is located at 300% axial chord.

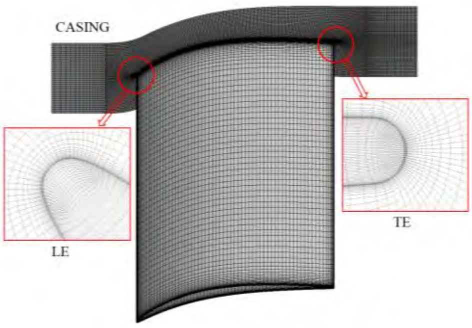


Fig. 2. Structured mesh of investigated compressor cascade

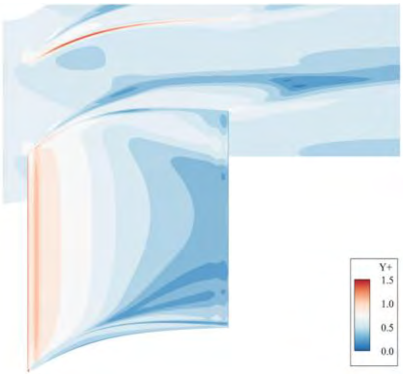
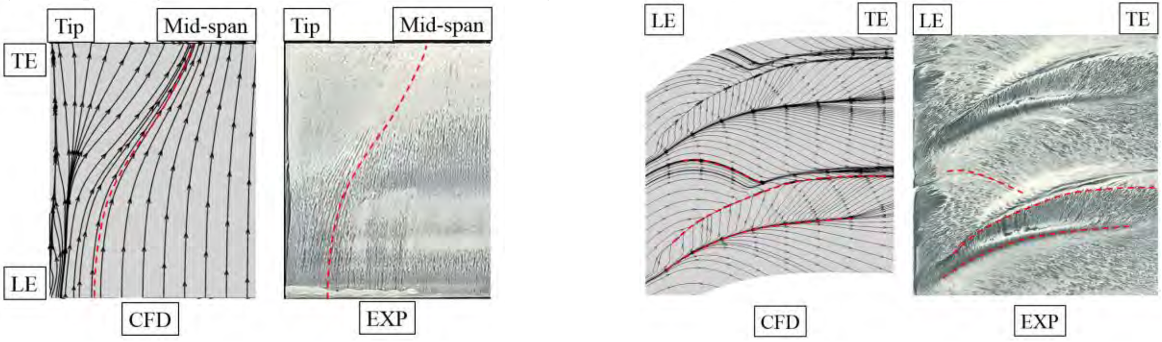


Fig. 3. Y+ contour

Structured mesh of the compressor cascade is created, showing in Fig. 2. The detail mesh inside blade tip, near leading edge (LE) and trailing edge (TE) is also showed in enlarged view. In order to capture tip region flow accurately, the spanwise the number of grid points inside tip clearance is 33. Otherwise, 'O' type mesh is created around blade and the mesh near wall surface is refined so as to increase the quality of the mesh and simulation accuracy of boundary layer flow respectively. As shown in Fig.3, Y+ near wall surface is around 1, which meets the requirement of turbulence model used in this study.

For further proving the accuracy of numerical method utilized in this study, experimental and numerical results are compared in Fig. 4. The results show that the numerical simulation can capture flow field at tip region with acceptable accuracy, also proving numerical method used in this study is suitable.



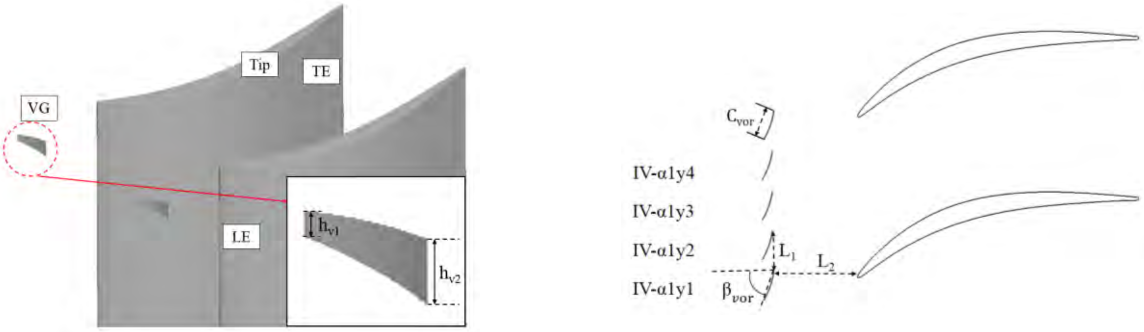
(a) Suction surface (b) Casing surface

Fig. 4. Comparison of experimental (EXP) and numerical (CFD) results

## GEOMETRY OF VORTEX GENERATOR

In order to investigate the effect of incoming vortex on TLVB of a compressor cascade, the vortex generator is utilized in this study to provide the incoming vortex. The 3D view and defination of VG is showed in Fig. 5. The VG has a whole annulus arrangement, and a section of it is shown in the blade-to-blade view. The height of the VG is 4% of the blade height.

In order to investigate the effect of pitchwise location and rotating direction of incoming vortex, different incoming schemes were designed by moving VG along pitchwise and changing the stagger angle of the VG. The distance between two adjecant VGs is a quarter of pitch of compressor cascade. The stagger angles are showed in Fig. 5(b), and they are noted as 'α1' (72 °), 'α2' (52 °), 'α3' (32 °) and 'α4' (12 °), respectively.



(a) 3D view of VG (b) blade to blade view

Fig. 5. Geometry and definition of VG

## RESULTS AND DISCUSSION

### *1 Control mechanism of incoming vortex on tip leakage vortex breakdown*

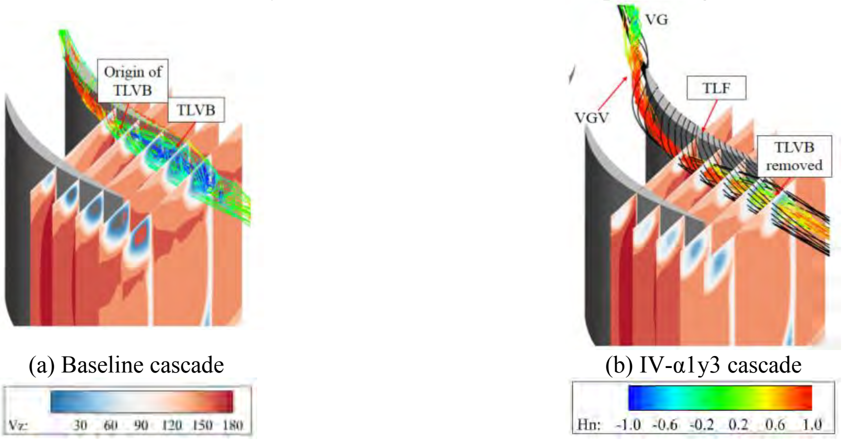
First of all, the effect of incoming vortex on TLVB is investigated at steady conditions. From all 16 incoming vortex schemes, only VG-α1y3 cascade can remove TLVB completely. Therefore, the flow field of VG-α1y3 cascade is compared with that of baseline cascade in this section to reveal the control mechanism of incoming vortex on tip leakage cortex breakdown.

Figure 6 shows the axial velocity contours and 3D streamlines with normalized helicity contours. The axial velocity which is higher than 0 is showed in the figure. The normalized helicity is defined in Equation (1), in which the ξv is vorticity vector and Vv is velocity vector. From Ref. [9], it can be known that the streamlines of TLV core with normalized helicity distributions are significantly helpful in investigating the change mechanism of tip leakage vortex breakdown.

$$Hn = \frac{\xi_V \bullet V_V}{|\xi_V| \bullet |V_V|} \qquad (1)$$

In Fig. 6(a), it shows that tip leakage vortex is formed at the leading edge of the compressor cascade tip, and it expands along streamwise. Near trailing edge of compressor cascade, a significantly reversed flow can be clearly seen and axial velocity is lower than 0 at core of TLV, indicating tip leakage vortex breakdown is occurred. From Hn distributions of TLV, the breakdown can also be clearly revealed. At upstream of TLVB region, the Hn is about unity, while it reduces rapidly when the TLVB is occurred. At downstream of TLVB, the TLV is regenerated as the Hn is increased. By utilizing vortex generator, a strong incoming vortex is introduced at upstream of compressor cascade, which can remove TLVB completely for scheme IV-α1y3.

From Fig. 6(b), the reversed flow is disappeared by introducing incoming vortex and axial velocity is also increased at TLV core. Different from baseline cascade, the tip leakage vortex of IV-α1y3 cascade is not derived from leading edge of compressor cascade, however, vortex core is replaced by incoming vortex induced by VG. The tip leakage flow is rolled up around the incoming vortex. The higher value of Hn is acquired for IV-α1y3 cascade, indicating that TLV of IV-α1y3 cascade is rolled up more tighter and has higher intensity than that of baseline cascade. Therefore, one of the reason for controlling tip leakage vortex breakdown by utilizing incoming vortex is that a vortex which has higher intensity than TLV of baseline cascade is introduced and the ability of TLV to withstand adverse pressure gradient is enhanced.



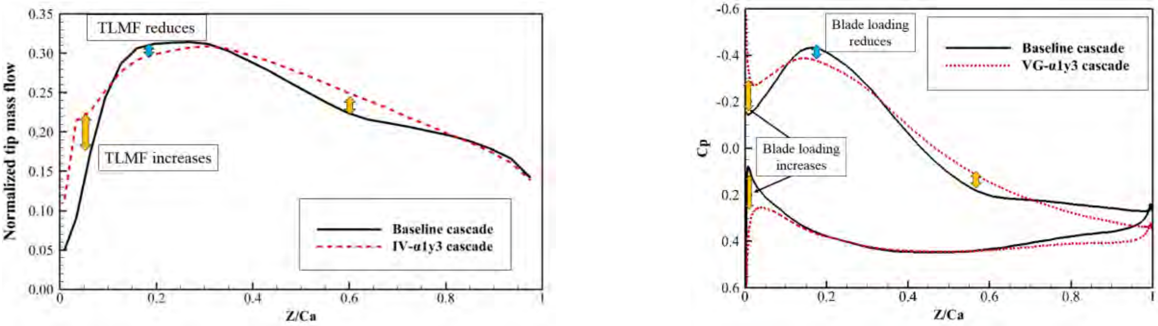
(a) Baseline cascade

(b) IV-α1y3 cascade

Fig. 6. Vz contours at different sections and 3D streamlines with dimensionless helicity contours

In order to further find out the effect of incoming vortex on the tip leakage flow, normalized tip mass flow and Cp distribution at 98% blade span is showed in Fig. 7. The region of maximum tip leakage mass flow is located about from 0.15 to 0.3 axial chord, which agrees well with the distribution of Cp. The tip leakage mass flow is almost direct proportion to blade loading near blade tip, proving that pressure gradient at blade tip is the driving force of tip leakage flow. The variation of tip mass flow by using incoming vortex is also agreed with that of Cp at blade tip. After utilizing incoming vortex, blade loading from about 0 to 0.15 axial chord and 0.32 to 0.7 is increased, which accounts for the increase of tip leakage flow in these regions. The increase of tip leakage mass flow near tip leading edge can enhance the strength of TLV, which is another reason for the reduction of TLVB [15]. Compared with baseline cascade, the adverse pressure gradient is more moderate for IV-α1y3 cascade, which is beneficial to the development of TLV.

In this section, the control mechanism of incoming vortex on TLVB is investigated. By utilizing VG, a strong incoming vortex is introduced, which becomes the vortex core of TLV and enhances the strength and ability to withstand adverse pressure gradient for TLV. Moreover, tip leakage mass flow near leading edge is increased because of the increase of blade loading near tip leading edge, coupled with the moderate adverse pressure gradient, the reduction of TLVB is achieved.



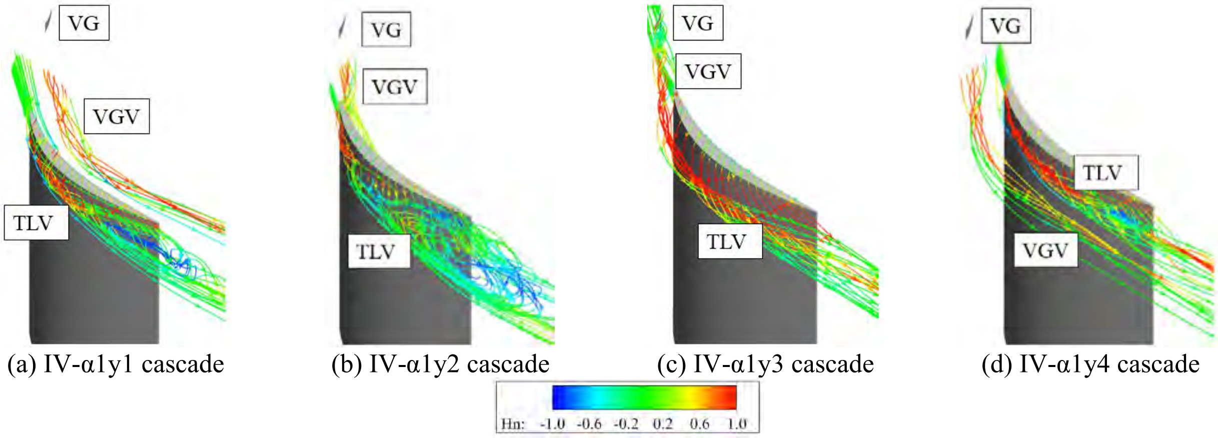
(a) Normalized tip mass flow

(b) Cp distribution at 98% blade span

Fig. 7. Distribution of flow parameters at tip region

Because the tip leakage vortex breakdown can be completely removed by IV-α1y3 cascade, the cascade is compared with other schemes to investigate the position effect and rotation direction effect of incoming vortex on TLVB in this section. The results will be the basis for unsteady investigation in the following sections.

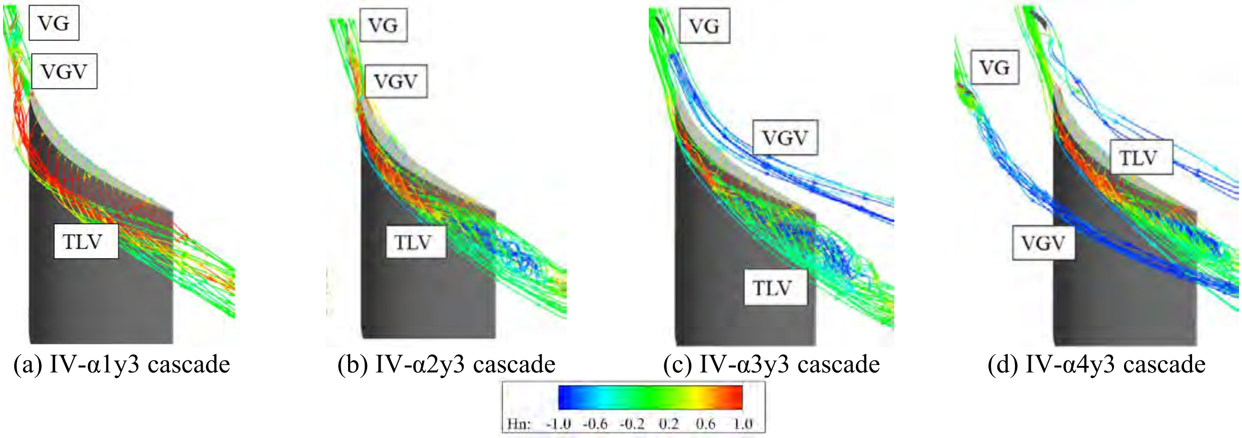
Figure 8 shows the comparison of 3D streamlines with normalized helicity contours with incoming vortex located at different pitchwise locations. Compared with baseline cascade in Fig. 6(a), it shows that only scheme IV-α1y3 cascade can remove TLVB. From helicity contours, it can be known that the rotation directions of incoming vortexes are the same as TLV. For IV-α1y1 cascade in Fig. 8(a), as the incoming vortex far away from TLV, there is a minor variation of TLVB. In Fig. 8(b), the TLVB is more severe than that of baseline cascade and IV-α1y1 cascade. It also can be seen from helicity contours that TLVB moves upstream due to the influence of incoming vortex. At position of scheme IV-α1y2, tip leakage flow at leading edge is disturbed by incoming vortex and there is no propagation of incoming inside blade passage. Hence, the formation of TLV is disturbed and TLVB is deteriorated. With the incoming vortex near suction surface and TLV, the TLVB is reduced as shown in Fig. 8(c) and Fig. 8(d).



(a) IV-α1y1 cascade (b) IV-α1y2 cascade (c) IV-α1y3 cascade (d) IV-α1y4 cascade

Fig. 8. 3D streamlines with normalized helicity contours (pitchwise position effect)

The angle effect of incoming vortex is also investigated in Fig. 9. The change of incoming vortex angle is achieved by varying stagger angle of VGs which are located at same positions with each other. It can be seen from 3D streamlines with normalized helicity contours in Fig. 9 that with the variation of incoming vortex angle, the flow trajectory of vortex also changes, which is the result of the variation of secondary flow affected by the incoming vortex. With the changing of stagger angle of VG from α1 to α4, the rotation direction of incoming vortex is reversed which can be observed by the reversed value of normalized helicity in vortex core. Compared with baseline cascade, it also can be seen that TLVB can be reduced by incoming vortexes with different rotation directions. However, the control mechanisms of different schemes differ from each other. The effect of incoming vortex with positive normalized helicity value has been discussed above. From Fig. 9(c) and (d), it can be seen that TLVB is reduced, especially for scheme IV-α4y3 cascade, the helicity in vortex core of TLV is increased significantly. The flow mechanism is that incoming vortex increases secondary flow near tip and passage vortex, hence, the shear stress between PV and TLV is increased, causing the increase of TLV strength. Therefore, the TLVB is delayed.



(a) IV-α1y3 cascade (b) IV-α2y3 cascade (c) IV-α3y3 cascade (d) IV-α4y3 cascade

Fig. 9. 3D streamlines with normalized helicity contours (rotating effect)

## *2 Effect of incoming vortex on tip leakage vortex breakdown at unsteady condition*

It is known that the incoming vortex in multiple stage compressor is ubiquitous, such as passage vortex, and moves along the circumference. In order to investigate the influence of incoming vortex on tip leakage vortex in compressor cascade, unsteady simulation is utilized and the incoming vortex moves along the circumference with movement velocity of 100 m/s. The 100 m/s was selected based on the value of velocity at inlet and there is a sliding plane between the VG domain and the compressor cascade domain. The interface between the two domains is a periodic repeat interface. In order to avoid the effect of moving wall to boundary layer, the side wall of vortex generator is set to slip boundary. Because of suppression of TLVB is achieved by scheme IV-α1y3 cascade at steady condition, the incoming vortex of VG with stagger angle of α1 is selected in this section. In order to keep the shape and strength of incoming vortex in relative coordinate system same as that at steady condition, the stagger angle of VG is adjusted by calculating velocity triangle. The time step in this study is $1.7875\times10^{-5}$. The flow field within compressor cascade is resolved with 20 equidistant steps for an incoming vortex passing.

Figure 10 shows comparison of blocking region with/without incoming vortex. It can be seen that the TLVB begins at about 0.62 axial chord and the blocking region is about 87% of the blade axial chord length. By utilizing incoming vortex, the TLVB is delayed and the blocking region is reduced significantly. Compared with baseline cascade, the axial blocking region is reduced by 31%, indicating incoming vortex can reduce TLVB even in unsteady condition. Different from steady condition, the utilizing of incoming vortex at unsteady condition can't remove TLVB which is because the existence of circumferential velocity of EV changes the shape of incoming vortex.

The effect of incoming vortex on pressure distribution at blade surface is showed in Fig. 11. It can be seen that the fluctuation of Cp near leading edge is strongest, and is decreased with the propagation of TLV. The variation of Cp from t=0/20T to t=5/20T and from t= 15/20T to t=0/20T is very dramatic compared with that from 5/20T to t=15/20T, indicating that the fluctuation near leading edge is mainly from interaction between incoming vortex and flow field near blade leading edge.

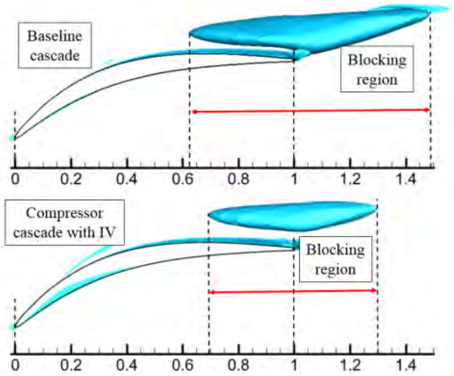


Fig. 10. Comparison of blocking region with/without incoming vortex (Vz=0)

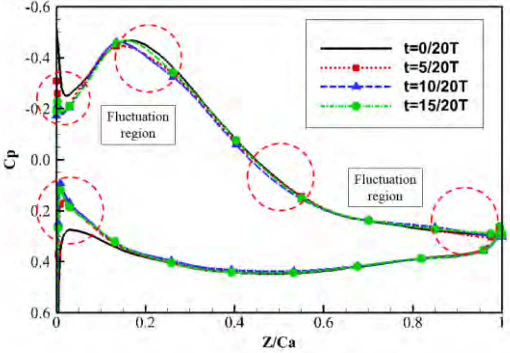


Fig. 11. Variation of Cp distribution

## CONCLUSIONS

Vortical incoming flow is an inherent flow character in compressors, which has significant effect on the downstream flow field. By utilizing endwall vortex generator, the steady and unsteady effect of incoming vortex on tip leakage flow and tip leakage vortex breakdown is investigated. The major conclusions are as follows:

(1) At steady condition, incoming vortex can completely remove TLVB for IV-α1y3 cascade. The flow mechanism is that a strong incoming vortex is introduced by utilizing VG, which which becomes the vortex core of TLV and enhances the strength and ability of TLV to withstand adverse pressure gradient. Moreover, tip leakage mass flow near leading edge is increased because of the increase of blade loading near tip leading edge, coupled with the moderate adverse pressure gradient, the reduction of TLVB is achieved.

(2) The pitchwise location and rotation direction of incoming vortex have significant effect on the interaction between incoming vortex and TLVB. For the incoming vortex with rotation direction being same as TLV, incoming flow angle is increased and the tip leakage mass flow will increase with incoming vortex near blade leading edge. However, the incoming vortex with opposite rotation exerts opposite effect. Increase of tip leakage mass flow near the leading edge is one of the reasons for reduction of TLVB but not the main reason for the disappearing of TLVB of IV-α1y3 cascade. For incoming vortex with rotation direction different from TLV, incoming vortex increases secondary flow near tip and passage vortex,

hence, the shear stress between PV and TLV is increased, causing the increase of TLV strength. Therefore, the TLVB is delayed.

(3) By utilizing incoming vortex at unsteady condition, the TLVB is delayed and the blocking region is reduced significantly. Compared with baseline cascade, the axial blocking region is reduced by 31%, indicating incoming vortex can reduce TLVB even in unsteady condition. Different from steady condition, the utilizing of incoming vortex at unsteady condition can't remove TLVB which is because the existence of circumferential velocity of EV changes the shape of incoming vortex.

## ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China (No. 51806174), and National Science and Technology Major Project (J2019-II-0011-0031).

## References

[1] J. C. Li, S. J. Geng, J. Du, H. W. Zhang, C. Q. Nie. Circumferentially propagating characteristic dominated by unsteady tip leakage flow in axial flow compressors [J]. Aerospace Science and Technology, 2019, 85: 529-543.

[2] S. Kang, C. Hirsch. Tip leakage flow in linear compressor cascade [J]. Journal of Turbomachinery, 1994, 116(4): 657-664.

[3] Y. F. Gao, Y. W. Liu. A flow model for tip leakage flow in turbomachinery using a square duct with a longitudinal slit [J]. Aerospace Science and Technology, 2019, 95: 105460.

[4] J. C. Li, J. Du, S. J. Geng, F. Li, H. W. Zhang. Tip air injection to extend stall margin of multi-stage axial flow compressor with inlet radial distortion [J]. Aerospace Science and Technology, 2020, 96: 105554.

[5] J. Du, F. Lin, H. W. Zhang, J. Y. Chen. Numerical investigation on the self-induced unsteadiness in tip leakage flow for a transonic fan rotor [J]. Journal of Turbomachinery, 2010, 132(2): 021017.

[6] A. P. S. Wheeler, T. Korakianitis, S. Banneheke. Tip-leakage losses in subsonic and transonic blade rows [J]. Journal of Turbomachinery, 2013, 135(1): 011029.

[7] X. J. Yu, B. J. Liu, H. K. Jiang. Characteristics of the tip leakage vortex in a low-speed axial compressor [J]. AIAA Journal, 2007, 45(4): 870-878.

[8] M. Furukawa, M. Inoue, K. Saiki, K. Yamada. The role of tip leakage vortex breakdown in compressor rotor aerodynamics [J]. Journal of Turbomachinery, 1999, 121(3): 469-480.

[9] M. Furukawa, K. Saiki, K. Nagayoshi, M. Kuroumaru, M. Inoue. Effects of stream surface inclination on tip leakage flow fields in compressor rotors [J]. Journal of Turbomachinery, 1998, 120(4): 683-692.

[10] C. Brandstetter, M. Jüngst, H.-P. Schiffer. Measurements of radial vortices, spill forward, and vortex breakdown in a transonic compressor [J]. Journal of Turbomachinery, 2018, 140(6): 061004.

[11] X. Y. Su, X. D. Ren, X. S. Li, C. W. Gu. Unsteadiness of tip leakage flow in the detached-eddy simulation on a transonic rotor with vortex breakdown phenomenon [J]. Energies, 2019, 12(5): 954.

[12] F. Soranna, Y.-C. Chow, O. Uzol, J. Katz. The effect of inlet guide vanes wake impingement on the flow structure and turbulence around a rotor blade [J]. Journal of Turbomachinery, 2006, 128(1): 82-95.

[13] A. P. S. Wheeler, R. J. Miller, H. P. Hodson. The effect of wake induced structures on compressor boundary-layers [J]. Journal of Turbomachinery, 2007, 129(4): 705-712.

[14] R. Mailach, I. Lehmann, K. Vogeler. Periodical unsteady flow within a rotor blade row of an axial compressor-Part II: wake-tip clearance vortex interaction [J]. Journal of Turbomachinery, 2008, 130(4): 041005.

[15] R. L. Ma, W. J. Devenport. Unsteady periodic behavior of a disturbed tip-leakage flow [J]. AIAA Journal, 2006, 44(5): 1073-1086.

[16] R. L. Ma, W. J. Devenport. Tip gap effects on the unsteady behavior of a tip leakage vortex [J]. AIAA Journal, 2007, 45(7): 1713-1724.

[17] R. L. Ma, W. J. Devenport. Unsteady aperiodic behavior of a periodically disturbed tip-leakage vortex [J]. AIAA Journal, 2008, 46(5): 1025-1038.