Research on the Adjustable Guide Vane in a Compressor Sector Cascade

W F Xu¹, P Sun² and G G Yang¹

¹ Dalian Maritime University, Dalian, China
² Civil Aviation University of China, Tianjin, China

E-mail: xuwenfeng@dlmu.edu.cn

Abstract. In order to simulate the inlet flow angle and Mach number of the tested blade, a row of guide vanes is set before the tested blade during the sector cascade experiment. In this paper, a kind of adjustable guide vane (AGV) is designed, which can rotate continuously and change the inlet flow angle of the tested blade conveniently and quickly. The variation rule of the clearance between the AGV and the end wall is introduced. The influence of the clearance on the flow field structure under different Mach number and incidence angle is studied by numerical and experimental methods. It is found that the clearance of the leading edge is small at the top and the root, and the leakage vortex is mixed with the passage vortex. The interaction between the leakage vortex and the passage vortex in the trailing edge results in the decrease of Mach number and the increase of flow angle at the AGV outlet. The clearance has little effect on the span of 20% - 80%. At the same incidence angle condition, with the increase of Mach number, the influence range of leakage vortex is expanded, and the variation magnitude of flow angle and Mach number at the top and root position is increased; At the same Mach number condition, with the decrease of the AGV rotation angle from positive to negative, the top clearance is increased gradually, and the root clearance is decreased gradually. The separation range at the top is expanded gradually, which results in the variation magnitude of flow angle and Mach number is increased, but the effect is opposite at the root of the AGV.

1. Introduction
With the high-speed development of the aerospace industry, there are more and more aerodynamic research methods for aero-engine, which are mainly divided into experimental research, theoretical analysis and numerical research. Wind tunnel experiment is one of the important research methods used to verify the correctness and reliability of the theoretical analysis and numerical calculation results, which has been widely used by researchers around the world [1]. The linear cascade can conveniently and quickly obtain some basic phenomena in supersonic and transonic cascades [2-3]. With the development of research on the three-dimensional flow field, the strong three-dimensional flow characteristics of the flow field in the linear cascade cannot be fully displayed [4-6]. In addition, the influence of inlet distortion on the performance of compressors needs to be studied through full-scale stage experiments [7]. However, the cost of the full-scale stage experiments is high, and the test method is difficult. Therefore, some researchers have made improvements on the basis of the linear wind tunnel to obtain the sector cascade wind tunnel, which made the measurement of the full three-dimensional flow field convenient and cheap [8-9].

In the process of wind tunnel cascade experiment, it is necessary to change the inlet Mach number and the flow angle of the cascade. The flow angle can be adjusted by changing the turntable of the tested rig in the linear cascade experiment [10-11]. In the sector cascade experiment, if the flow angle needs
to be changed, it is necessary to machine the tested blade with different stagger angles [12]. Liu J M et al [13] used the rectifier cascade to achieve the change of inlet flow angle during the study of turbine guide vane on the sector cascade. Li L L [14] and Sun P [15] et al. first proposed a sector cascade test method, in which a guide vane was installed before the stator to simulate the inlet flow conditions of the stator in the compressor stage. Sun P et al. [16] found that the clearance between the guide vane and the end wall would affect the outlet flow field and the test results in the sector cascade experiment with adjustable guide vanes. Tian C R et al [17] found that the leakage flow interfered with the main flow during the study of the effect of top clearance on the performance of the axial-flow fan, which affected the performance of the fan. Wu Y H et al [18] found that reducing the mixing of top leakage flow and secondary flow in the passage can increase the flow rate and reduce the flow loss of the compressor. In addition, it was found in the previous studies that the leakage vortex generated by the clearance can make the vortex structure change significantly at the top of the compressor stator, affecting the aerodynamic parameters of the outlet [19-20]. Therefore, an adjustable guide vane is designed in this paper, which can rotate around the rotation axis. The contact surface of the guide vane fixed block and the end wall is designed as spherical surface to reduce the clearance. Experimental and numerical methods were used to study the effect of leakage vortex on the flow field structure of the top and root under different Mach numbers and incidence angles.

2. Experimental facility and the guide vane structure

2.1. Sector cascade tunnel
The experimental investigation was carried out in a transonic wind tunnel, as shown in Fig.1. The wind tunnel is a continuous open jet type wind tunnel. After the compressed air passes through the steady flow section, it is accelerated through the contraction section and finally enters the test section.

![Figure 1. Sketch of wind tunnel](image)

The physical picture is shown in Fig. 2. The sector cascade consists of 15 adjustable guide vanes with a circumferential angle of 110°. The flow field was measured within the range of 8° circumferential angle of the middle outlet. The distribution of measurement points is shown in Fig. 2, there are 25 positions in the spanwise and 17 positions in the pitchwise, with a total of 425 measurement points.
2.2. The structure of the AGV

The schematic diagram of the AGV is shown in Fig.3. The stator represents the tested blades. The AGV is fixed on the end wall through the fixed block, and the AGV can rotate with the central axis of the fixed block. The inlet flow angle of the tested blade can be changed by means of the adjustment of the AGV stagger angle. The adjustment direction of the stagger angle is clockwise seen from the top, the incidence angle of the stator is defined as positive, otherwise, it is negative.

As shown in Fig. 4, the meridian of the passage is straight, resulting in bumps and clearances between the fixed block and the end wall during the rotation of the AGV. Therefore, the meridian of the hub and casing is modified to a circular arc. Similarly, the meridian of the fixed block is also replaced by an arc, as shown in Fig. 4. ORI and OPT respectively represent the prototype and the modified structure. These two arcs take R1 and R2 as radii and take point e as the center, respectively, passing through points a (c) and b (d). The modified structure can make the fixed block fit the passage and eliminate the clearance, as shown in Fig. 5.
However, limited by the solidity of the cascade, the fixed block cannot completely connect the top and root of the AGV, as shown in Fig. 6. There is still a clearance between the top and root of the AGV and the end wall. As the AGV is rotated, the clearance size also is changed, as shown in Fig. 7. As the incidence angle of the AGV decreases from positive to negative, the top clearance is increased gradually, while the root clearance is decreased gradually.

After measuring the AGV clearance, it is found that the top clearance height of the leading edge is 0.5mm, the root clearance height is 0.3mm. There is no obvious change in the height of the clearance along the chordwise. The top clearance height of the trailing edge gradually increased from 0.5 to 1.4mm along the chordwise, and the root clearance height gradually increased from 0.4 to 1.3mm. According to the actual clearance height, the calculation model is modified to ensure that the structure of the actual model is approximately the same as the calculation model.

Figure 5. Structure diagram of the fixed block

Figure 6. Structure diagram of the AGV

Figure 7. The clearance of the AGV
3. Numerical procedures

3.1. Numerical simulation methods

All of the numerical results presented in this paper were obtained by ANSYS CFX software. The meshes used in the investigation were generated by the grid generator ANSYS ICEM. The hexahedral structural meshes were generated in O-type topology. As shown in Fig.8, the calculation domain mesh corresponding to the physical structure of the piece is given. All of them had a similar structure, the total number of nodes was between 16 and 18 million. To ensure the accuracy of calculation, the $y^+$ adjacent to the wall was approximately 10 to meet the need of the k-ε turbulence model. No-slip adiabatic wall condition was defined on the blade and end wall. The inlet pressure profile obtained from the cascade experiment was specified at the domain inlet. The static pressure (101325Pa) was used to set the outlet boundary condition.

![Figure 8. Computational mesh](image)

3.2. Periodicity of the sector cascade

In this paper, the No.8 AGV in the middle region of the sector cascade is selected to analyze the flow field. In order to explore the repeatability of the flow field structure between the No.8 AGV and the adjacent blades, the aerodynamic parameter distribution of the cascade outlet is shown in Fig. 9. From Fig. 9(a), it can be found that there are three complete flow passages in the analyzed section, corresponding to No. 7, No. 8, and No. 9 AGV respectively. As shown in the contour of the Mach number and flow angle, there is no significant difference in the range and distribution of the corner region and wake area of each blade outlet.

The circumferential distribution curves of Mach number and flow angle at different spans are shown in Fig. 9(c). The outlet parameters corresponding to the three blades change periodically, which has good repeatability at different spans. It is verified that the flow field structure of the analyzed blades and the adjacent blades is approximately the same, and the aerodynamic parameters in the central region of the sector cascade are periodically distributed.

![Figure 9. Outlet parameters](image)
In order to validate the accuracy and reliability of the simulation method, the experimental and computational results were compared. The distribution of the flow angle and Mach number at the AGV outlet is shown in Fig.10. Due to the limitation of the test equipment, only the flow field structure in the span of 5-92% was measured during the experiment. It can be seen from the contour that the two results are almost the same, and there is a low-speed region with a large flow angle near the end wall. Compared with the experimental and numerical results, the maximum difference of flow angle is larger than that of Mach number, and the maximum difference is 12% near the tip of the AGV. It can be found from the pitch average curve that spanwise distributions of the experiment are similar to the numerical. The Mach number curve has the same change trend in the range above 65% span, but the difference in flow angle is large. In general, the numerical methods are reliable and can be used for the prediction of the aerodynamic performance in this study.
4. Results and discussion

4.1. The effect of the AGV clearance on the flow field

Fig. 11 shows the contour and the pitch average curve of Mach number and flow angle at the outlet of guide vane when the incidence angle is 0°. The clearance leads to a low Mach number region at the top and root of the AGV, and the flow angle increases in the corresponding range. From the pitch average curve of the flow angle, it can be found that the clearance has little effect on the range of 17%-92% span. The flow angle increases significantly in the range above 92% span and below 7% span, while the flow angle value is slightly larger than that without clearance in the span of 7%-17%. From the pitch average curve of Mach number, the leakage flow results in the reduction of Mach number in the range above 79% and below 20%. Moreover, the influence range of clearance on the Mach number along the span is larger than the flow angle.
Figure 11. Aerodynamic parameter of the AGV outlet

In order to study the influence of guide vane clearance on flow field structure in detail, Fig. 12 displays the 3D vortex structure in the AGV passage visualized by the iso-surface of Q and renders the iso-surface with the Mach number. It can be found that the clearance leads to the creation of a leakage vortex at the top (TLV) and root (RLV) of the AGV. The leakage flow between the top and the root of the leading edge is mixed with the suction branches of the horseshoe vortex to form the passage vortex. The leakage vortex squeezes out the passage vortex (PV) and narrows its influence range at the top and root of the trailing edge of the AGV. Therefore, it can be found that the leakage vortex has a significant effect on the vortex of the passage vortex. But it has little effect on the location and range of the concentrated shedding vortex (CSV) at the outlet. The outlet flow angle deviates from the main flow direction under the action of the cross secondary flow of the leakage vortex, resulting in the increase of the flow angle and the decrease of Mach number near the top and root.
4.2. The effect of the AGV clearance at different Mach number on the flow field

The pitch average curve of flow angle and Mach number at different Mach numbers conditions is shown in Fig. 13. The Ma = 0.4 and no Ma = 0.4 respectively represent the results of guide vanes with and without clearance when Mach number is equal to 0.4. As shown in Fig. 13 (a), with the increase of Mach number, the flow angle difference of the guide vane with or without clearance increases gradually in the span above 92%. However, the clearance causes a small change in flow angle with the Mach number under the 17% span. In the span of 17% - 92%, the flow angle of the guide vane with or without clearance is almost the same under different Mach number conditions, and the clearance has no obvious influence on the range.

(a) Flow angle
(b) Mach number

Figure 13. Aerodynamic parameter of the AGV outlet at different Mach number conditions

It can be seen from Fig. 13(b) that the clearance has little effect on the Mach number in the span of 20% - 79% under different Mach number conditions. The effect mainly exists at the hub and casing. With the increase of Mach number, the difference of Mach number of the same span increases gradually in the span of above 79% and below 20%. The maximum difference is 5.31% when the Mach number is equal to 0.4, and it increases to 5.85% when Mach number is equal to 0.6.

Figure 14 shows the 3D streamlines, the total pressure recovery coefficient contour, and secondary streamlines of the guide vanes at different Mach number. The color of the 3D streamline represents the Mach number. With the increase of Mach number, the speed of leakage flow increases, the strength of leakage vortex increases slightly, and the loss caused by leakage increases. The influence range of leakage vortex increases along spanwise, which leads to the decrease of Mach number around the end wall. The effect of clearance on the concentrated vortex is small, so it has little effect on the aerodynamic parameters in the span of 20%-79%.
Figure 14. The 3D Streamlines, the total pressure recovery coefficient contour and secondary streamlines of the guide vanes at different Mach number conditions

4.3. The effect of the AGV clearance at different incidence angle on the flow field

As the AGV incidence angle decreases from positive to negative, the top clearance gradually increases and the root clearance gradually decreases. Fig. 15 shows the pitch average curve of the outlet Mach number and flow angle when the incidence angle is +6°, 0°, and -6°. The P6, P0, and N6 shown in the figure respectively represent the results of guide vane when the incidence angle is +6°, 0° and -6°. It can be seen that clearance has no effect on the flow angle in the span of 18% - 90%. Above 90% span, with the decrease of incidence angle, the increasing variation magnitude of flow angle increases gradually, and the change is opposite under 18% span. From Fig. 15 (b), it can be found that the clearance has no significant effect on the Mach number in the span of 19% - 80%. The influence of
clearance on Mach number under 19% span is larger than that above 80% span. With the decrease of incidence angle, the variation magnitude of the Mach number decreases near the root.

It can be seen from Fig. 16 that as the incidence angle decreases, the separation range of the leakage vortex increases gradually at the top of the AGV outlet, while that decreases gradually at the root. The leakage vortex causes the airflow to deviate from the main flow direction near the end wall, which results in the increase of the flow angle compared with that of the guide vane without clearance. Under different incidence angle conditions, the leakage vortex has a significant inhibitory effect on the passage vortex. Although the separation range of the passage vortex is reduced, it can be found from the 3D streamline that the leakage flow causes the airflow mixing resulting in a reduction in airflow velocity near the end wall. In addition, the clearance has little effect on the middle region of the flow passage, and there is no obvious change in the position and range of the wake and the concentrated shedding vortex.
Figure 16. The 3D streamlines, the total pressure recovery coefficient contour and secondary streamlines of the guide vanes at different incidence angle conditions

5. Conclusions
The adjustable guide vane (AGV) is designed based on the transonic sector cascade wind tunnel. The variation rule of the AGV clearance is introduced. And the influence of the clearance on the flow field structure is studied by numerical and experimental methods. The results are summarized as follows:

1) The clearance between the AGV and the end wall is inevitable. The contact surface between the fixed block and the end wall is designed as a spherical surface to reduce the clearance.
2) Limited by the solidity of the cascade, there is still a clearance between the top and root of the AGV and the end wall. As the incidence angle of the AGV decreases, the top clearance gradually increases and the root clearance gradually decreases.
3) The clearance has no significant effect on the flow field structure in the span of 20% -79%. The leakage vortex leads to the increase of the flow angle and the decrease of the Mach number near the top and root of the AGV. The influence of the clearance on the Mach number is wider than the flow angle. With the increase of Mach number, the variation magnitude of the flow angle and Mach number gradually increases near the casing and hub.
4) The clearance has no obvious effect on the flow field structure in the span of 19%-80% under the same Mach number and different incidence angle conditions. With the decrease of the incidence angle, the top clearance gradually increases, which leads to an increase of the leakage vortex and the variation magnitude of the flow angle and Mach number. The rule is just the opposite at the root.

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