Chapter 5
Flow Mechanism in Turbine Rear Frame Ducts

5.1 Geometrical and Aerodynamic Characteristics of Turbine Rear Frame and Their Development Trends

From the perspective of structure, turbine rear frame (TRF) is a part of the engine's load supporting system, which is designed to support the low-pressure rotor. From the perspective of aerodynamics, it is a component of the flow passage, connecting the low-pressure turbine with the exhaust nozzle, and thus it is also called exhaust casing. Figure 5.1 shows the meridian shape and geometry of TRF. In geometry, TRF is an annular pipe, and the diameters of its two ends are close; along the streamwise direction, its inlet connects to the low pressure turbine, and its outlet connects to the exhaust nozzle. Similarly, the inner casing of TRF is called hub, and there are outlet guide vanes (OGVs) between the hub and the casing. These OGVs have the functions of supporting, providing pathways for pipelines, and controlling flows. From the perspective of aerodynamics, OGVs are mainly designed to convert the outlet flow of the low-pressure turbine to axial flow at the cost of lowest total pressure loss, and meanwhile, to prevent flow separation in a wide range of working conditions. Because pipelines need to pass through the OGVs, both their minimum thickness and the 3D modeling methods are restricted. As a result, OGV design is the one of the major difficulties in TRF design. In addition, noise reduction and other factors should also be considered in TRF design.

The design objectives of modern aero-engines are to reduce weight and cost, increase turbine load, and decrease the number of stages. As a result, the inlet guide vanes of TRF always have high inlet prerotation, which makes it more difficult to carry out aerodynamic design for TRF. The structural requirements and the objective of weight reduction always result in complex 3D characteristics of TRF and engine mount recesses. For this reason, TRF designers are paying more and more attention to the influence of complex endwall geometries and engine mounting.

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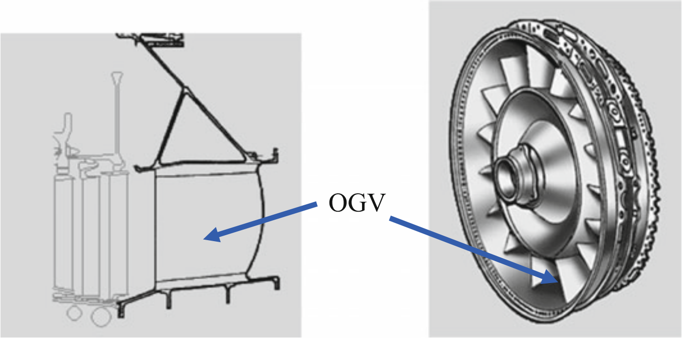


Fig. 5.1 Meridian shape (*left*) and geometry (*right*) of TRF

Table 5.1 TRF duct parameters of high-bypass-ratio turbofan engines

	CFM56-7B	GE90	E3 PW	LEAP-X	GEnx
Aspect ratio	0.99	0.98	1.06	–	1.06
Number of vanes	16	14	30	19	–
Turning angle	–	About 25	43.4	–	–
Inlet reynolds number	–	–	2.88×10^5	–	–
Inlet mach number	–	–	0.503	–	–
Outlet mach number	–	–	0.372	–	–
Tangential lean or not	Yes	No	No	Yes	Yes

Geometrical and aerodynamic parameters of TRF duct of some high-bypass-ratio turbofan engines are listed in Table 5.1 [1].

As can be seen from the table, OGVs in TRF of the current high-bypass-ratio civil engines have relatively small aspect ratio, generally less than 1.2. As a result, secondary flows are strong in the flow passage. For the purpose of weight reduction, the number of OGVs in a TRF is generally less than 20, and thus the relatively low solidity brings challenges to flow control. What’s more, rear engine mounts are placed on the TRF, and for the consideration of strength, the mounts are designed to be recessed into the casing to the depth as much as 30% of the inlet passage height of the TRF. However, this geometry may result in flow separation, weaken flow control effect, and seriously influence the aerodynamic performance of the TRF duct. In addition, tilted OGVs are often used in TRF. The reason for this design is that high thermal expansion of the OGVs would result in relative circumferential rotation between the hub and the casing, which can effectively reduce the thermal stress on the casing. Studies in recent years showed that tangentially-tilted OGVs, which intersect with the upstream wakes at a certain angle, can “cut” the wakes, and contribute to reducing the noise of the low-pressure turbine. Therefore, the tangentially-tilted structure has been adopted in many high-bypass-ratio civil engines in recent years. However, this structure would result in an corner area between the OGVs and the casing or hub, where flows tend to deteriorate, and it also brings new challenges to the aerodynamic design.

From the point of aerodynamic design of turbines, improvement of low-pressure turbine efficiency would effectively increase the overall efficiency of the engine and significantly reduce specific fuel consumption. In order to improve low-pressure turbine efficiency, the outlet flow angle of the low-pressure turbine always has a great deviation from the axial direction, which reaches 30° or even higher in some cases. Undoubtedly, this would increase the difficulty in OGV design. Meanwhile, TRF duct is located downstream of the low-pressure turbine and its flow conditions are influenced by the distribution of flow at the outlet of the upstream component, so it is difficult to guarantee flow control effect and meanwhile prevent flow separation in all the working conditions.

Generally speaking, the main geometrical and aerodynamic characteristics of TRF include small aspect ratio of OGVs, few in number, hangers recessed into the casing, tangentially-tilted OGVs, large turning angle of airflow, and low Mach number at the inlet and low Reynolds number, etc.

5.2 Influence of Geometrical Parameters on Flow Structures and Performance

The number of OGVs is restricted by the requirements of structural strength and weight reduction. As the downstream unit of the low-pressure turbine, the dimensions of its inlet are known, and its outlet dimensions should be limited to a range (with the outlet area basically the same as the inlet area), so as to guarantee low Mach number and reduce leaving-velocity loss. Geometrical parameters of TRF inlet and outlet have small range of choice, and more attention should be given to meridian profile, OGV profile parameters, hanging structure in TRF, and blade surface deformations, which would influence flows in TRF ducts and its performance.

5.2.1 Influence of Meridian Profile of Duct

The meridian profile of the TRF duct has significant influence on flow field distribution, and the influence of different meridian profiles on flows is shown in Fig. 5.2. The modified casing profile moderately narrows down after the thickest point of the OGV, and the hub profile is adjusted to a form of first expanding and then narrowing down so as to match with the changes in OGV thickness. As can be seen from the figure, the modifications have some effects in improving the flow capacity of the TRF duct, reducing the total pressure loss, and changing the flow

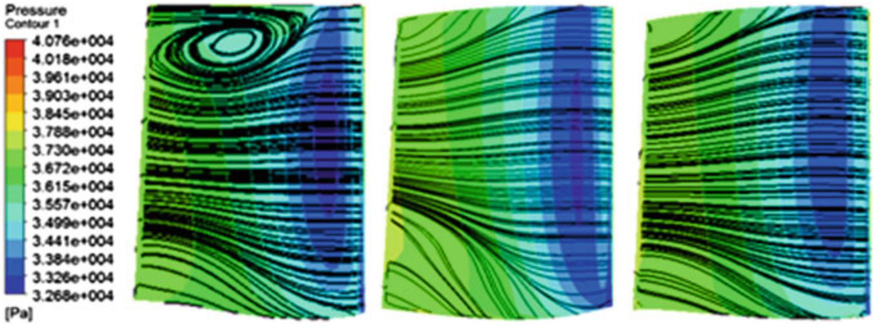


Fig. 5.2 Pressure distribution and limiting streamlines on the suction surface of the cases before and after modifications (*left* original profile; *middle* modified profile 1; *right* modified profile 2)

angle. The streamlines in the figure show the good effects of the modification of the casing profile, with flow separation disappeared completely and secondary flows only existing near the endwall regions. The hub modified profile 1 is not suitable because the range of secondary flows at the blade root shown in the figure increases obviously. From the load distribution at the blade root, it can be seen that there is a strong adverse pressure gradient after the leading-edge suction peak, but the expansion segment of the meridian hub profile in modified profile 1 is so long that it is still in the state of local deceleration after the suction peak; under the situations of deceleration and pressure gradient, the development of secondary flows accelerates obviously. In modified profile 2, the meridian hub profile is adjusted and the expansion segment is shortened. The end point is located near the leading-edge suction peak. It tries to improve the pressure gradient and slow down the development of secondary flows by the local acceleration after the suction peak. With respect to the performance parameters, the total pressure losses of the two modification modes are basically the same, but the streamlines suggest the range of secondary flows at the blade root decreases obviously in modified profile 2. In addition, the pressure distribution in modified profile 2 indicates the radial pressure gradient gets mitigated; the outlet flow angle is reasonably distributed, and the main flow is almost converted to axial flow.

5.2.2 Influence of OGVs' Profile Parameters

OGV profiling is somewhat restricted due to the influence of the oil supply pipe on the blade profile of the OGV. Thus, the influence of blade loading and thickness distribution is mainly discussed in this section.

(1) Influence of blade loading distributions

Sonoda et al. carried out a series of studies on the aerodynamic design of blade profile for TRF. They focused on studying small-scale aero-engines, which only have one low-pressure stage with low bearing requirement for the vanes, so the inlet Mach number of the TRF designed by them was much larger than that of high-bypass-ratio civil engines. In addition, the thickness of the vanes changed little. In spite of this, their design philosophy of blade profile is still useful for reference.

In 2008, Sonoda et al. designed an outlet guide vane cascade by adjusting the blade loading distribution, and concluded that, at low Reynolds number, extreme front loaded pressure distribution(ES) is more helpful to improve the vanes' aerodynamic performance than the conventional controlled diffusion airfoils (CDA) [2]. Experiments on the cascade were carried out at two working conditions respectively with high and low Reynolds numbers, and numerical simulation verification and analysis were performed as well. The experiments were carried out on the high-speed cascade testing rig of Honda Aircraft Company, and the numerical simulation was performed by using the inhouse RANS solver. The $k-\omega$ turbulence model was used at the high-Reynolds-number condition, and the SST turbulence model, supplemented by $\gamma-\theta$ transition model, was used at the low-Reynolds-number condition. The main design philosophy is about making the flow decelerate rapidly at the leading edge of the OGV by extreme front loading and thus inducing boundary layer transition earlier, so as to avoid the additional flow loss caused by laminar separation bubbles. As shown in Fig. 5.3, both the numerical simulation and experimental results suggested the loss caused by the CDA blade at low Reynolds number increased dramatically, while the loss caused by the ES blade at low Reynolds number stayed at low level; the low loss caused by the ES blade, which was significantly less than that by the CDA blade, over a wide range of attack angles.

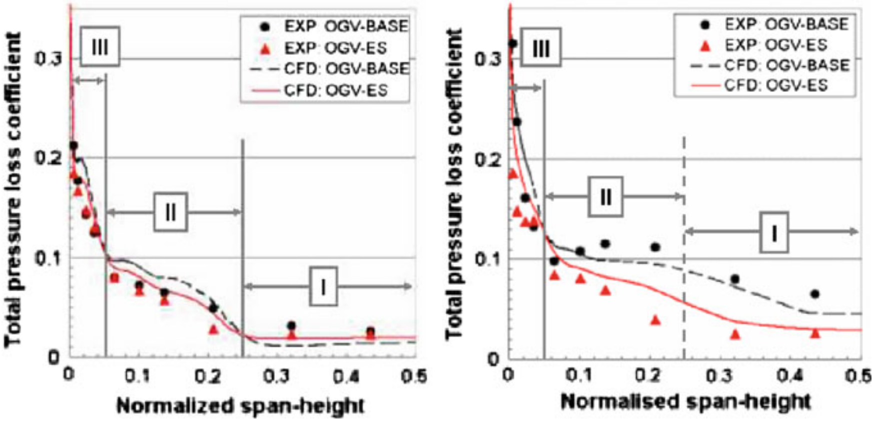


Fig. 5.3 Loss distribution at the OGV outlet in different blade loading forms [2] (*left* Re = 8.6 × 10^5; *right*: Re = 1.2 × 10^5)

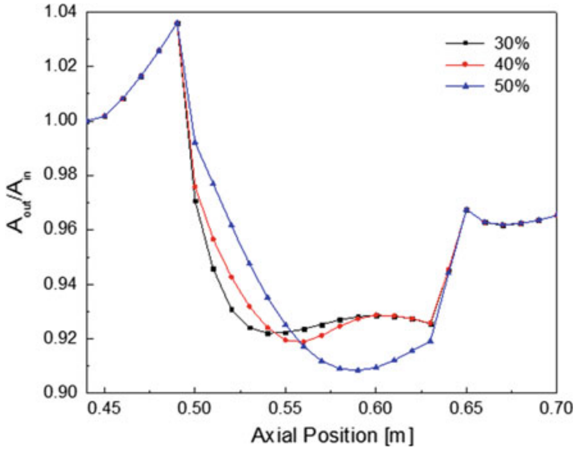


Fig. 5.4 Flow area distributions with different OGV thickness distributions

(2) Influence of thickness distribution

The flow fields in a TRF duct with three different thickness distributions of OGV were numerically investigated. When the thickest position moved from 30% of the chord length to 40%, the overall parameters of the TRF changed very little. However, when the position further moved to 50% of the chord length, the turning ability of the flow decreased to some degree. The backward moving of the thickest position of the OGV means the contraction of the front of the flow passage becomes slow and the acceleration capability of the leading edge becomes weaker. When the position further moved to 50% of the chord length, flow separation occurred near the trailing edge, which was the main reason for the insufficient turning angle of the flow.

Figure 5.4 shows the flow area distributions in the TRF duct with different OGV thickness distributions. As can be seen from the figure, the backward moving of the thickest position resulted in longer contraction section of the flow passage and weaker acceleration capability of the leading edge, and further reduced the minimum flow area. Under the condition of constant outlet area, after the flow area reached to the minimum, the area expanding gradient would become larger, thus causing the increase of the adverse pressure gradient in the expansion section of the flow passage, which resulted in the flow separation.

5.2.3 Influence of Hanging Structure

Several rear engine mounts (3–5 in general) are installed on the outer wall of the TRF. For the consideration of structural strength, the mounts are generally designed to be recessed towards the flow passage of the TRF to the depth as much as 30% of the inlet passage height of the TRF, so as to reduce the bending moment on the

TRF. The hangers recessed towards the flow passage of the TRF may result in flow separation and the resulting great flow loss, and have negative influence on OGVs' flow control effect. These factors would all result in the decrease of TRF's aerodynamic performance.

In 2007, Hjarne et al. from Chalmers University of Technology studied the influence of hangers on flows and losses in a TRF through experimental investigations and numerical validation [3]. Figure 5.5 shows the measurements of outlet flow angle at the location 0.8 chord length from the outlet section of the OGV, and the hanging depth accounted for about 18.5% of the blade height of the TRF. Due to the influence of the hanging structure, the underturning of the flow with 1 degree deficit is formed near the casing, and the underturning angle kept increasing and reached to the maximum (about 2°) at about 75% of the blade height. Then, the influence of the hanging structure gradually reduced with the increase of the distance to the wall surface, and the underturning angle returned back to 1° at the middle blade section. The experimental results suggest that the hanging structure has significant negative influence on OGVs' flow control effect.

From the spanwise loss distribution at the outlet section, it can be seen that the flow loss at the outlet was generally decrease from the casing to the middle blade section. This is mainly because the hanging structure influenced the vortex structure close to the casing, and the thicker boundary layer caused larger flow loss. Then, the loss reached to the minimum in the area about 0.025–0.04 m from the wall surface, where the wakes were thinnest, and increased again in the area about 0.04–0.07 m from the wall surface because the rapid increase in thickness of the wakes brought about additional flow loss (see Fig. 5.6).

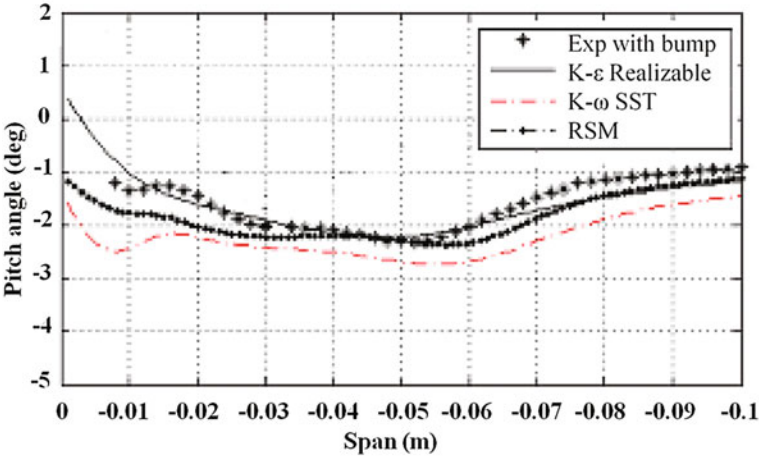


Fig. 5.5 Distribution of outflow angle [3] (from the casing to the middle blade section)

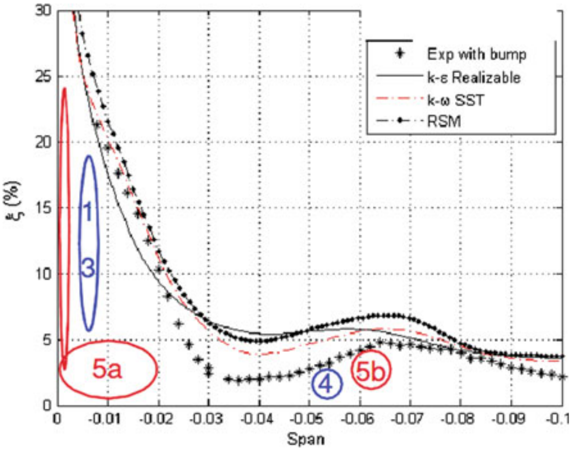


Fig. 5.6 Spanwise distribution of flow loss at the outlet section [3]

5.2.4 Influence of OGV Surface Deformations

According to the data from Volvo Aero Corporation, geometric deformations similar to welding spots would be formed on the surface of TRF of the main high-bypass-ratio turbofan engines in the process of assembly. In addition, considering the severe working conditions of the engines, high temperature erosion and other factors would also result in geometric deformations of TRF in their service period, which may make their aerodynamic performance worse. To study the potential influence of the deformations on TRF, Chernoray et al. from Chalmers University of Technology carried out an experiment study on the influence of geometric deformations in 2010 on the low-speed cascade testing rig, and performed numerical simulation for detailed analysis [4].

Figure 5.7 shows the outlet total pressure loss distributions of deformations at different positions, which can be used in quantitative analysis of deformations' influence on the flow loss in TRF. As can be seen from the figure, deformations at all the positions increased the flow loss ununiformly. However, except for the deformation near the suction peak, which caused a sharp rise in flow loss, deformations at the other positions had little influence. As can be seen from both the loss distribution and wake distribution, deformations had little influence on the near-wall boundary layer, and the additional flow loss was mainly distributed in the region from the middle of the blade to 80% of the blade height.

To find out the sensitivity of the flow in TRF to deformations, 3D numerical simulations were carried out for deformations with a diameter of 3 mm and 5 mm respectively. Both the deformations were located in the 20% axial area where their influence could reach to the highest. Figure 5.8 shows flow structure on the OGV surface with different sizes of deformations, where the red area represents the backflow area (where the axial velocity was less than 0). The comparison showed that the size of deformations had significant influence on the OGV's aerodynamic performance. When the diameter increased from 3 to 5 mm, a large range of corner

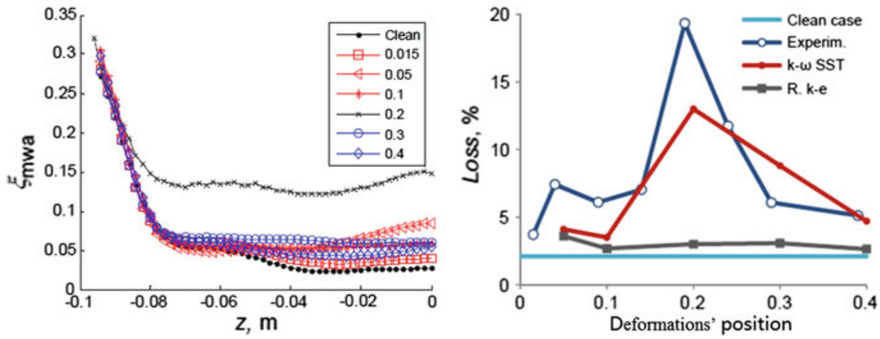


Fig. 5.7 Outlet total pressure loss distributions of deformations at different positions [4]

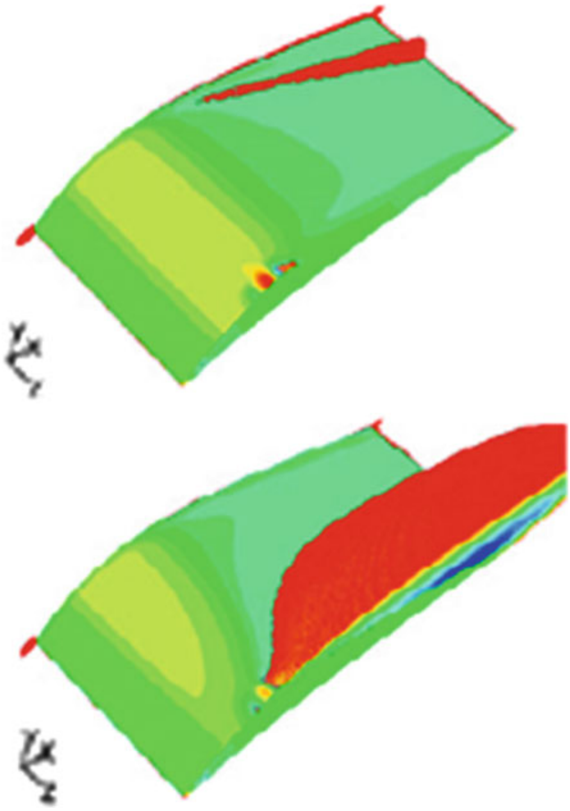


Fig. 5.8 Flow structures near the OGV with different sizes of deformations

separation was generated near the casing. The following conclusions can be reached: (1) the position of a deformation is the most important influencing factor, which has the largest influence on the flow, so one should try hard to prevent deformations from being generated near the suction peak at the leading edge of the

OGV suction surface; however, the influence of deformations at any position of the pressure surface is very small or even can be neglected; (2) for the deformations at the front of the suction surface of the OGV, their size has significant influence on the OGV's aerodynamic performance; however, for the part insensitive to deformations, even the relatively large deformations have very small or even negligible influence on the flow over the OGV.

5.3 Influence of Aerodynamic Parameters on Flow Structures and Performance

TRF ducts are required to be operating at a wide range of working conditions. Changes of aerodynamic parameters, which are caused by changes of working conditions of the upstream low-pressure turbine, would also influence flows in TRF ducts. The influence of inlet flow angle, turbulence intensity, and inlet Mach number is mainly discussed in this section.

5.3.1 Influence of Inlet Flow Angle

Among inlet conditions, inlet flow angle is one of the most important influencing factors. In order to increase low-pressure turbine efficiency, the outlet flow angle of the low-pressure turbine always has a great deviation from the axial direction, which reaches 30° or even higher in some engines. As a result, the turning angle of the OGVS of TRF should be large.

In 2006, Hjarne et al. carried out an experimental investigation on the low-speed cascade testing rig of Chalmers University of Technology [5], and gave a detailed analysis of the outlet flow field of the TRF ducts as well as the vortex structure. The experimental operating conditions were close to the actual OGV parameters, and parameters were measured at three working conditions, in which the inlet flow angle was respectively 30° (design condition), 20°, and 40°. The main measured parameters included streamwise vorticity and outlet loss distribution.

Figure 5.9 shows the load distribution on the OGV surface. When the inlet flow angle decreased, the load on the OGV would decrease, and so would the strength of vortex systems in the OGV passage and the strength of interaction between the vortex systems. When the inlet flow angle increased, the load on the OGV would increase, so would the strength of vortex systems in the OGV passage and the strength of interaction between the vortex systems. Meanwhile, the load increase would also result in the increase of adverse pressure gradient on the suction surface of the OGV, increase of transverse pressure gradient in the passage, and flow separation on the suction side of the OGV. Figure 5.10 shows the vorticity distribution at the outlet of the TRF passage. As can be seen from the figure, the inflow angle had influence on both the strength of secondary flows in the TRF passage and the vortex structure.

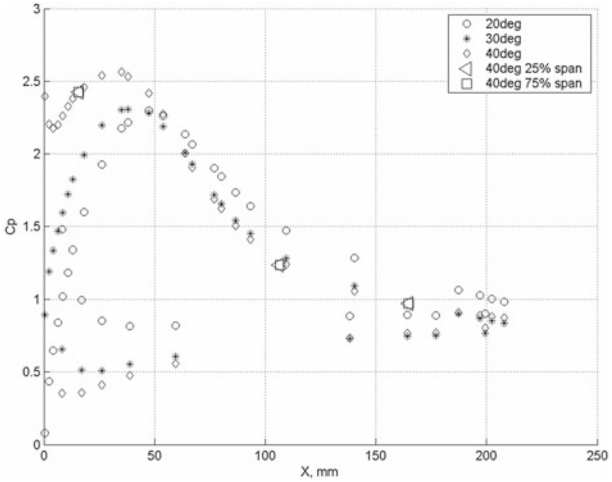
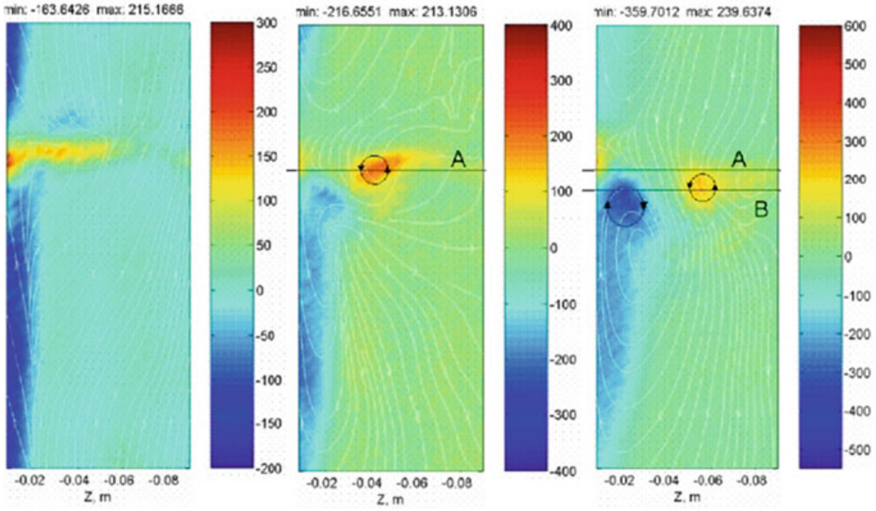


Fig. 5.9 OGV loading distribution at different inlet flow angles [5]



Flow angle: **20**°   Flow angle: **30**°   Flow angle: **40**°

Fig. 5.10 Vorticity distribution at the outlet of the OGV passage at different inlet flow angles [5]

Researchers from Chalmers University of Technology carried out experiments on a TRF duct testing rig, compared the experimental results with numerical simulation results, and studied the influence of off-design conditions on flows and losses in TRF ducts [6]. Off-design conditions were defined as the conditions when the inlet flow angle plus or minus 10° from the design point; the inlet Reynolds number was 2.8×10^5; the inlet flow angles in the three conditions were

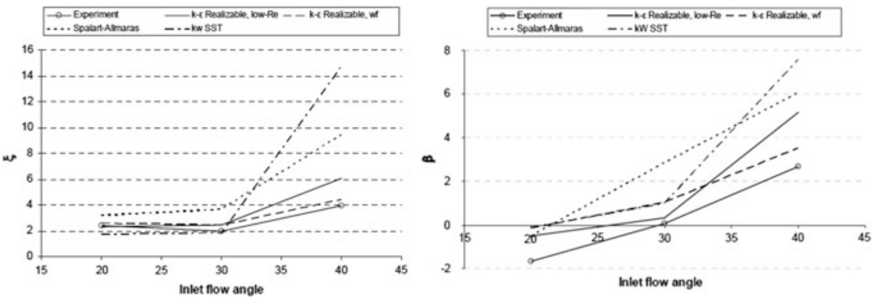


Fig. 5.11 Outlet loss distribution (*left*) and outlet flow angle distribution (*right*) at different inlet flow angles [6]

respectively 20°, 30° (design point), and 40°; the turbulence intensity was 5%. The major measured parameters included blade loading distribution, downstream wake distribution, and loss distribution.

Figure 5.11 shows the outlet loss distribution and outlet flow angle distribution at different inlet flow angle conditions. As can be seen from the figure, the flow loss at off-design points was higher than that at the design point, and the flow loss in the condition with increased deflection angle increased significantly. In the working condition with the inlet flow angle of 40°, the experimental result suggested the outlet flow was underturned by 3 degree, and nearly all the numerical simulation results of losses and flow angles in the off-design conditions were significantly higher than the experimental results.

5.3.2 *Influence of Turbulence Intensity*

In 2006, Hjarne et al. carried out experiments on the low-speed cascade testing rig of Chalmers University of Technology, and investigated the influence of turbulence intensity on the flow field in the TRF [6]. Changes in turbulence intensity were achieved by setting up a turbulence grid on the upstream. Flows in two turbulence intensity conditions, 5% and turbulence intensity 0.5%, were investigated.

Figure 5.12 shows the loss distribution at the outlet of the TRF duct at different turbulence intensity. With the increase of turbulence intensity, the interaction between vortex systems was enhanced. From the point of loss, in the low turbulence intensity condition, the interaction between vortex systems was relatively weak, and the non-uniformity of the loss distribution was much more obvious than that in the high turbulence intensity condition. However, with the increase of load, the influence of turbulence intensity on flow field characteristics decreased.

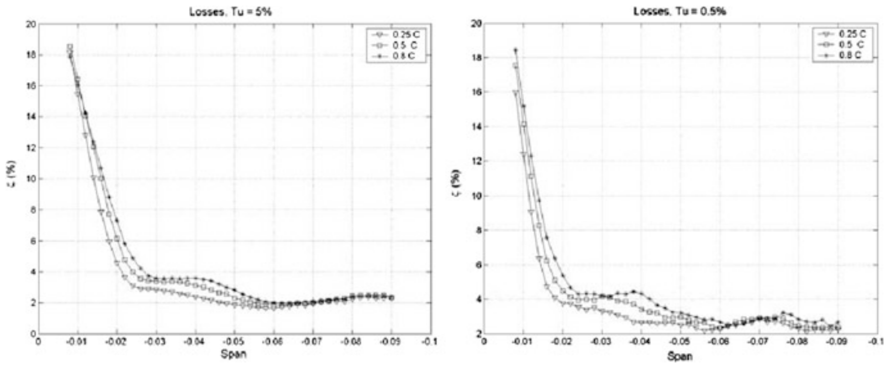


Fig. 5.12 Influence of turbulence intensity [6]

5.3.3 Influence of Inlet Mach Number

In 2006, Sonoda et al. [7] studied two different kinds of OGVs through experiments and numerical simulation. At different angles of attack, the influence of different inlet Mach numbers, especially high Mach numbers, on flows and losses in TRF ducts was studied. The range of the Mach numbers was from 0.5 to 0.87; the range of the attack angle was from −6° to 1.5°; Re number was 1.2×10^5. The research results are shown in Fig. 5.13. In the design condition, the loss increased with the increase of the Mach number at a slow rate; at off-design points, the loss increased rapidly with the increase of the Mach number. This trend was even more obvious when using CDA profiles.

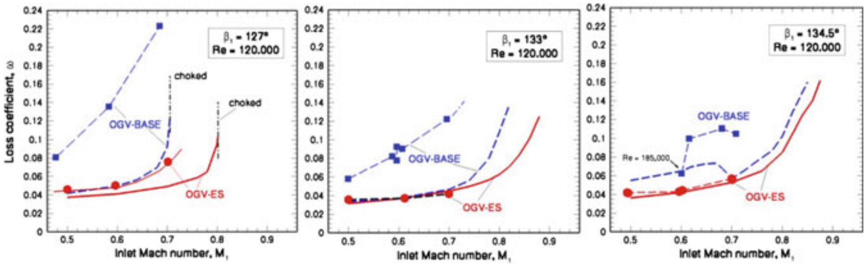


Fig. 5.13 Influence of inflow Mach number on losses at different attack angles [7]

5.4 Methods for Designing TRF Ducts with Large Turning-Angle OGVs

In terms of aerodynamic characteristics, a TRF duct with OGVs is actually similar to a row of compressor guide vanes with extremely low solidity, which operate at low Reynolds number and low Mach number, if difference in thickness and other special factors are neglected. Comparatively speaking, the degree of freedom in aerodynamic design of TRF is very low. Generally, the number of OGVs has been determined by the requirements of structural strength and weight reduction before aerodynamic design. Because the oil supply line is contained in the OGVs, the maximum thickness and stack mode have also been determined. As the downstream unit of the low-pressure turbine, the aerodynamic boundary conditions and geometrical parameters of its inlet are known, and the geometrical parameters of its outlet should be limited to a range (with the outlet area basically the same as the inlet area), so as to guarantee low Mach number and reduce leaving loss. Therefore, OGV profile and meridian passage profile are the main parameters that need to be designed. TRF ducts have two functions in aerodynamics. The first function is flow control. TRF ducts should adjust the outlet flow of the low-pressure turbine to better conditions; specifically, they should make the outlet flow direction to the axial direction, keep outlet Mach number in a reasonable range to reduce leaving loss, and provide uniform distribution of outlet flow. The second effect is noise reduction. The noise at the outlet of the low-pressure turbine could be reduced by adopting reasonable OGV layout (tangentially tilted) and using the unsteady effect of the upstream low-pressure turbine rotor and OGVs. Therefore, the following four guidelines should be followed in aerodynamic design of a TRF duct: the flow loss in the TRF duct itself should meet the qualification; the TRF duct should incur little interference to the unsteady potential of the upstream low-pressure turbine components; it should produce good flow control effects, including uniform outlet flow field, axial outlet flow, and proper outlet Mach number; it should also play a role in noise reduction.

5.4.1 Design of Duct Profile

When selecting meridian profile for a TRF duct, the following two points, which take into account the influence of different meridian profiles on flows in a TRF and its performance, should be considered:

(1) The casing profile moderately narrows down after the thickest point of the OGV. The local acceleration caused by the meridian passage contraction is expected to reduce the separation at the expansion segment in the rear part of the passage, which results from adverse pressure gradient.

(2) The hub profile matches with the changes in OGV thickness and the lowest point is set near the thickest point, so as to improve flow area distribution by means of area compensation.

5.4.2 Design of OGV Profile

OGV profile selection is restricted by the inner oil supply line, so the maximum thickness and stack mode have been almost determined. Thus, selection of blade loading distrubutions, or thickness distributions in terms of design parameters, should be mainly considered.

The flow area in the second half of the TRF passage expands rapidly due to the rapid decrease of OGV thickness after the thickest point, and thus there is relatively strong adverse pressure gradient in the flow field. Extreme Font-loaded distrubution is helpful to reduce the transverse pressure gradient in the expansion segment and avoid flow separation in the second half of the flow field. Meanwhile, the extreme font-loaded form can induce boundary layer transition very early, thus helping to avoid the additional flow loss caused by laminar separation bubbles. To realize the extreme font-loaded distribution, the thickest position should be placed at the front as far as possible. In this way, the axial distance to the upstream rotor will be small, so the leading-edge radius should not be too large, so as to avoid enhancing the potential interference to the upstream rotor. In addition, relatively high trailing edge thickness is helpful to improve the pressure gradient in the second half of the flow passage.

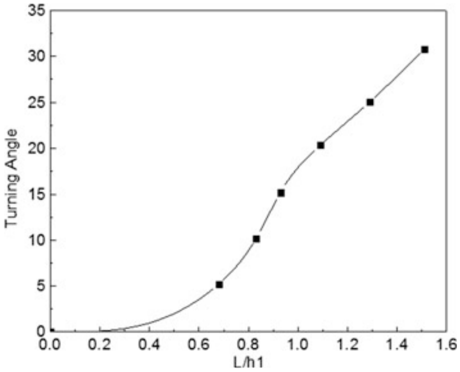
Except for the size-uniformity scheme, the non-uniformity scheme with both large and small OGVs can also be used. The basic purpose of the scheme is to separate the OGVs as supporting structures and the OGVs for guiding flows. Because supporting struts are responsible for supporting load and providing pathway for pipelines, they have higher maximum thickness and are not allowed to bear high bending. However, large thickness means greater aerodynamic loss for the guide vanes. To reduce design difficulty, increase design space, and further lower structural weight and flow loss, the supporting struts should be designed as “large struts” with large chord length and thickness, and the guide vanes should be designed as “small struts” with small chord length and thickness. In this way, the large struts can meet the structural requirements, and the small struts can meet the aerodynamic requirements for flow control as far as possible through the 3D profiling techniques, such as using skewed or swept blades.

For the small struts, their trailing edge should be flush against that of the large struts in the axial direction, so as to ensure they are located in the same slot where the large struts are located. Because the small struts have shorter chord length, in the case of large deflection angle, their separation-resisting capability is lower than that of the large struts. Keeping the trailing edge flush can reduce the actual attack angle of the small struts, decrease the load, and avoid separation. In addition, this measure can also effectively decrease the load on the rear part of the large struts, reduce the overall adverse pressure gradient on the large struts, and lower the risk of flow separation on the large struts. Their circumferential positions should be determined based on the inlet conditions. In general, the passage should be kept at basically the same degree of convergence, and the small struts could be placed uniformly in the passage of the large struts. In the case of large turning angle, the small struts could be shifted towards the suction surface of the large struts, so as to reduce the adverse pressure gradient on the suction side of the large struts and thus lower the risk of flow separation on the large struts.

5.4.3 Selection of Axial Length of the Duct

There is almost no area expansion in TRF ducts, so the most important geometrical parameter is axial length (dimensionless). Shortening the axial length is helpful to reduce engine weight. The axial length of the TRF is mainly determined by its aerodynamic load, namely the turning angle. Figure 5.14 presents the relation between load and the geometrical parameter of a TRF duct. As can be seen from the figure, with the increase of the inlet flow angle, the aerodynamic load of the TRF increases and larger relative length is required accordingly. However, the relation is not linear; the larger the inlet flow angle, the higher the required increment of relative length will be. It should be noticed that the inlet boundary conditions used here are in linear distribution. However, in actual engines, the outlet aerodynamic parameter of the low-pressure turbine is always poor in uniformity, and thus the relative length required for flow control is often larger. Therefore, by taking the curve as a boundary, the lower right area of the boundary is regarded as the “safe area”, while selecting the parameter from the upper left area may result in larger possibility of flow separation.

Fig. 5.14 Relation between turning angle and axial length of TRF ducts



References

1. Turner, M. G. (2000). *Full 3D analysis of the GE90 turbofan primary flowpath [R].* NASACR-209951.
2. Sonoda, T., Schreiber, H. A., & Arima, T. (2008). *Endwall performance of outlet guide vane cascades with different blade loading distributions [R].* ASME Paper GT2008-51111.
3. Hjärne, J., Chernoray, V., & Larsson, J. (2008). *Experimental investigations and numerical validation of an outlet guide vane with an engine mount recess [R].* ASME Paper GT2008-50168.
4. Chernoray, V., Ore, S., & Larsson, J. (2010). *Effect of geometry deviations on the aerodynamic performance of an outlet guide vane cascade [R].* ASME Paper GT2010-22923.
5. Hjärne, J., Larsson, J., & Löfdahl, L. (2006). *An experimental investigation of secondary flows and loss development downstream of a highly loaded low pressure turbine outlet guide vane cascade [R].* ASME PaperGT2006-90561.
6. Hjärne, J., Larsson, J., & Löfdahl, L. (2006). *Performance and off-design characteristics for low pressure turbine outlet guide vanes: measurements and calculations [R].* ASME Paper GT2006-90550.
7. Sonoda, T., & Schreiber, H. A. (2007). Aerodynamic characteristics of supercritical outlet guide vanes at low reynolds number conditions [J]. *Journal of Turbomachinery, 129*(4), 694–704.