20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

The Influence of Endwall Contouring and Fillet Shapes on the Performance of Transonic Turbine Stage Nozzle Guide Vane

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Abstract

The present study is intended to investigate numerically the effect of fillet and axisymmetric endwall shapes on loss reduction in a highly loaded low aspect ratio transonic turbine stage. The fillets and endwall contouring shapes are applied over nozzle guide vanes. The aerodynamic performance of two contoured endwalls with and without fillets are studied and results are compared with the base case (cylindrical endwall). The 3D viscous compressible analysis is carried out using commercial CFD Code CFX-14.5 using SST k-ω turbulence model. Maximum reduction of 30.6% in mass averaged total pressure loss coefficient is achieved for endwall contour having S-type variation along with fillet.

Introduction

One of the main objectives that drive the design of highly efficient gas turbine engine is to have less secondary flow losses in their flow passages irrespective of their stage. It comprises of a horse-shoe, passage, and corner vortices, considered detrimental to the performance and reliability of gas turbines [1]. These circulatory flows result in stagnation pressure loss and they hold a considerable part of total stagnation pressure losses (30-50%) [2] in low aspect ratio blading i.e. high-pressure stages. This may seriously affect its efficiency as well as the performance of downstream turbine rotor. Looking at the methods available for reducing the secondary flow losses, contouring of endwalls received a significant attention due to its effectiveness in reducing secondary flow losses. Contouring of endwalls is of two types; axisymmetric and non-axisymmetric and it can be applied on one or both endwalls. Even though non-axisymmetric contouring of endwalls shows effectiveness in the reduction of aerodynamic and endwall heat transfer, it is generally applied to turbine blade endwalls [3] and is not discussed further here. Past researchers have showed that tip side meridional contouring (axisymmetric) is one of the most effective methods to improve the performance of the low aspect ratio turbine nozzle guide vanes. Dejc et al.[4] reported the potential benefits of this design feature initially with design rules to achieve it and later followed by subsequent works. Kopper et al.[5] investigated the effect of endwall contouring in a linear nozzle cascade with one planar and one contoured endwall at an exit Mach number of 0.85. Profiled endwall showed 17% reduction in mass averaged loss relative to the planar case and this improvement is mainly from the reduction of secondary loss on the planar wall side of the cascade. Boletis [6] published an experimental investigation on the effect of tip endwall contouring on the three-dimensional flow field in a low aspect ratio annular turbine nozzle guide vane having an aspect ratio of 0.6 and reported a reduction of transverse pressure gradients at the frontal part and inward migration of low momentum fluid over the suction surface. Regarding the effect of tip side endwall contouring on transonic/supersonic nozzle guide vane, Moustapha and Williamson [7] tested two endwall contours having 'S' and conical shape variation over a range of exit flow conditions from subsonic to supersonic. Thicker hub loss region with significant under turning at transonic speed was experienced by conical shape compared to 'S' variant.

Though much insight is gained from the previous studies on the application of meridional endwall contouring on aerodynamic characteristics, investigations on endwall contouring and corresponding secondary flow mechanisms for transonic flow remains unclear. The objective of the present computational investigation is to gain a better understanding of meridional contouring and leading edge fillet on transonic turbine nozzle vane and their influence on secondary flow field.

Endwall and Fillet Design

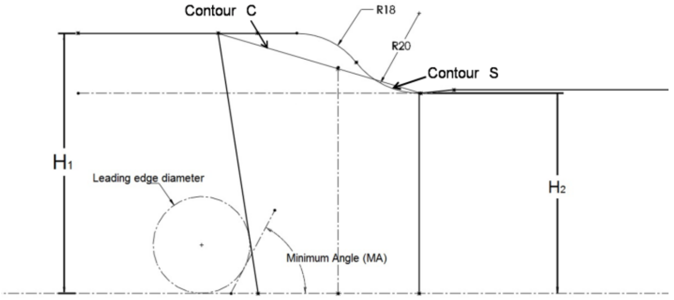


Figure 1. Fillet and meridional endwall profile design

Nozzle guide vane used in the present study is designed for a highly loaded turbine stage which does most of the flow turning near the leading edge. Salient features of the vane are as follows: Hub to tip radius ratio (R_h/R_t) = 0.84, Span at exit (H_2) = 50.115mm, axial chord and chord length at midspan = 45.87mm and 73.69mm respectively with vane count of 34.The objective of the present meridional contouring on tip side is to achieve the flow turning near the leading edge with low velocities to reduce the transverse pressure gradient and to reduce the radial migration of inflow boundary layer towards the midspan. Two different configurations of tipside endwall having variation in meridional profiling in terms of different rate of acceleration is investigated (Figure 1). Contour C employs linear variation while the other contour has S shape profile which starts at Z/Ch_{ax}=40% by having a concave curvature in the first half followed by convex curvature. Lower radius is given for concave part to have more acceleration rate. Present low aspect ratio NGV (H_2/Ch=0.65) have constant hub radius of 236.94mm. Tip radius at the inlet and outlet (329mm and 314.06mm) are selected based on the recommendations of Dejc et al [4]. It results in the contraction ratio (CR) of 0.3. Contraction ratio (CR) is defined as the difference in height at inlet and outlet divided by outlet height. This ratio lies close to the optimum value. Further fillets near the leading and trailing edges are modeled using shape parameters like leading edge radius and minimum angle. For a given leading edge radius, circle tangent to NGV is drawn which fixes the height where the fillet starts. Further with the help of minimum angle value, the connecting point between the arc and endwall is made resulting in 2D profile. Final fillet geometry is created by sweeping the 2D profile along the whole geometry of NGV at their endwalls. The radius of 5mm and 0.5mm is used at leading edge and trailing edge respectively and the corresponding contours are named as Cf and Sf .

Numerical Setup

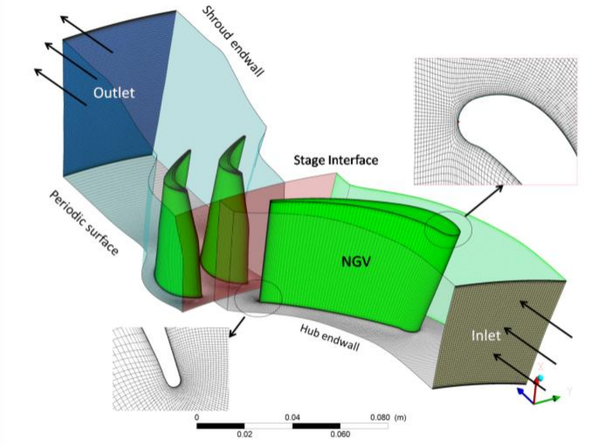


Figure 2. Computational domain of HP turbine showing salient features of boundary condition and mesh details

Computational evaluations on steady state three-dimensional viscous flow are carried out using finite volume code ANSYS CFX-14.5. The numerical procedure utilized for the present study is verified and validated against the experimental results of VKI-LS89[8] and E-TU/4 test case[9]. Validation test cases are selected on the basis of capturing the transonic flow phenomena's and stage performance parameters which are having strong three-dimensional flow. The structured mesh of high-quality hexahedral elements is generated using AutoGrid5, Numeca by maintaining non-dimensional near wall distance Y^+ less than 3. Around 4.5 million nodes with approximately 1.5 million nodes per blade passage is used for generating computational domain. This mesh density provides the grid independent solution. Computational domain of high-pressure turbine having one NGV and two rotor blade passages with their salient boundary surfaces, mesh resolution near leading edge and trailing edges is shown in Figure 2. The pitch-wise averaged total pressure and total temperature distribution along the span with a turbulent intensity of 8% is specified as the boundary condition at inlet while static pressure is specified at the outlet. Higher order resolution schemes are used for resolving spatial and turbulent quantities. Figure 3 shows the comparison of numerical results with experimental traverse data. Figure 3a shows the pressure loading at two different Mach numbers corresponding to 0.84 and 1.02. Figure 3b shows the comparison of flow angle and loss coefficient associated with the stator and rotor exit. Fair agreement between numerical and experimental results is seen.

Results and Discussions

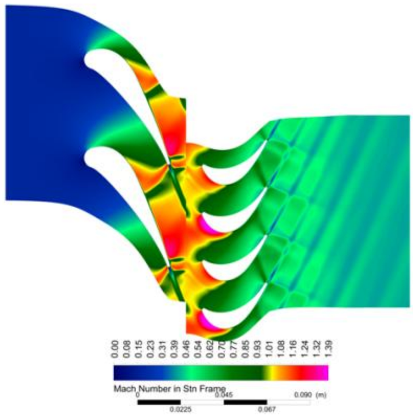
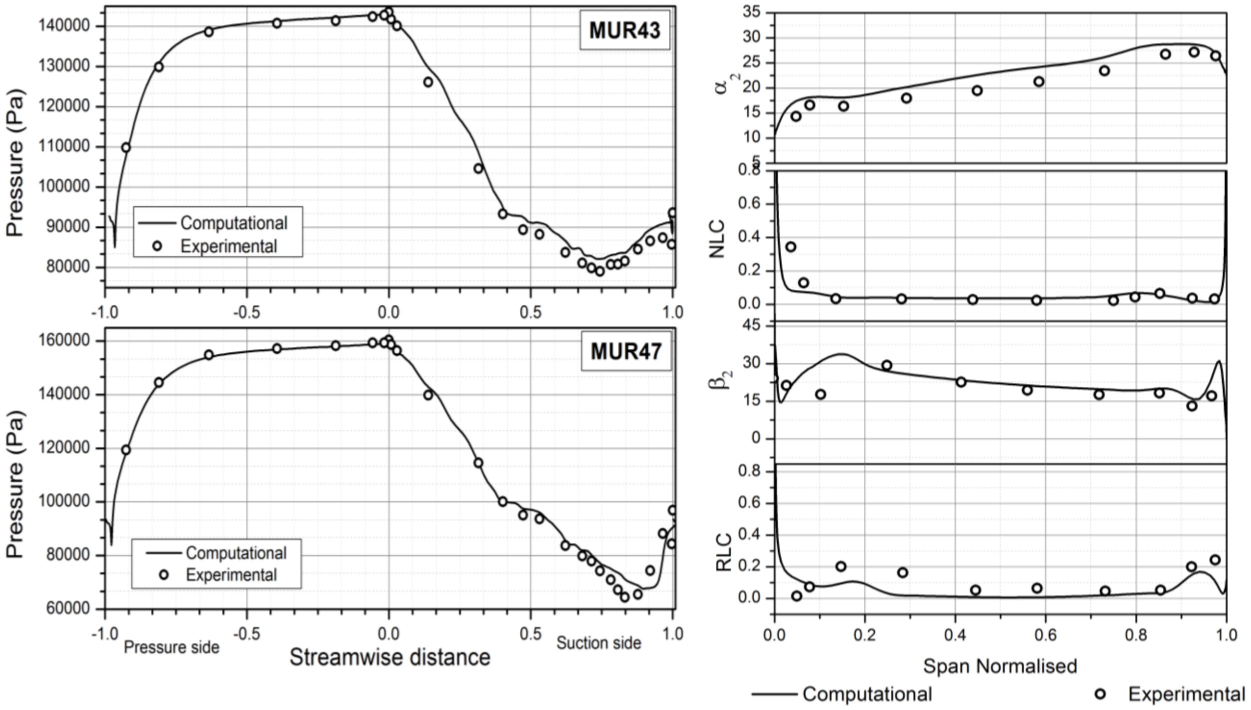


Figure 4. Mach number contours at midspan

Present high pressure turbine stage is designed for a stage pressure ratio of 2.78 and stage loading of 1.9 operating at 15976rpm. Mach number contours (stationary frame of reference) at midspan (Figure 4), indicate that the flow accelerates from subsonic to transonic velocities in the nozzle guide vane and rotor blade passages by attaining sonic condition at the throat i.e. choking of vane.



(a) (b)

Figure 3. Validation details of (a) VKI-LS89 profile (b) E-TU/4 test case

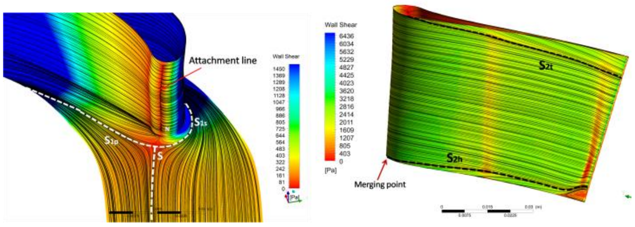


Figure 5. Flow features of HP turbine at (a) Midspan (b) Near Leading edge (c) Suction surface

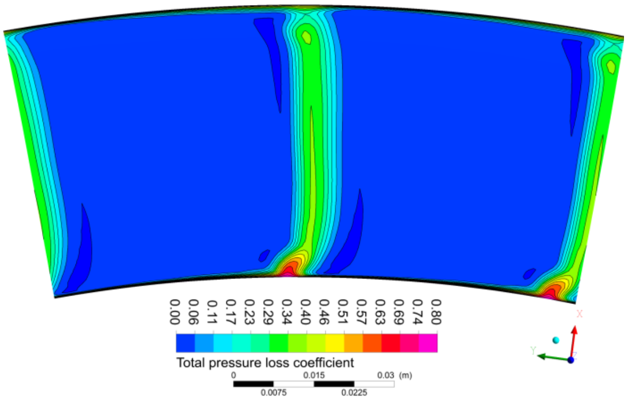


Figure 6. Total pressure loss coefficient at vane exit

This strong expansion to high local Mach number results in transonic flow features like normal shock, trailing edge shocks, their deflection and reflection with adjacent vane/rotor blades. Reduction in Mach number to subsonic confirms the presence of normal shock inside the vane passage. Secondary flow field associated with vane passage is discussed in Figure 5. As the incoming boundary layer approaches the vane passage it gets lifted up from the surface at saddle point (S) into two legs of HS vortex. As the skin-friction lines tend to converge toward the separation line in a separation process, limiting streamlines are plotted near the suction surface to study it. Separation (detachment) line (S1) is formed ahead of the vane, associated with the saddle point (S). Zero wall shear values confirm its position. Separation lines associated with the two legs, pressure and suction side HS vortex (S_{1p} and S_{1s}) are shown in Figure 5. Merging of two legs due to traverse pressure gradient followed by radial movement of separation lines (S_{2h}& S_{2t}) towards the midspan is clearly seen. Area enclosed between the endwalls and the separation lines (S_{2h}& S_{2t}) have significant three-dimensional flow due to the growth of passage vortex and corner vortex. The intensityof this three-dimensional flow region is replicated in stagnation pressure loss (Figure 6).

Effect of endwall contouring and leading edge fillet on secondary flow field

Figure 7 presents the blade loading at three different spanwise positions (5% (near hub), 50% and 95% (near tip)) of the vane for different endwall contours. Effect of contouring is felt throughout the vane height with significant variation in the tip region when compared to midspan and hub. Further, suction side variations are more prominent when compared to pressure surface for all the cases. From Figure 7c, it is evident that S contour performs better near tip region in 0- 60% of an axial chord than C contour by creating pressure rise, thereby unloading the front part of the vane. This results in reduced traverse pressure gradient which acts as the driving force for secondary flows. Since vane is designed as an aft-loaded one, this effect does not provide any significant reduction in loss between two contours. Further in the rear part, intense acceleration creates low pressure region near the tip compared to midspan helping in the reduction of flow distortion and radial inflow of low momentum fluid.

Figure 8 shows the variation of pitch averaged total pressure loss coefficient at the vane exit plane. Significant reduction of total pressure loss is achieved by endwall contouring throughout the vane span when compared to the base case due to a reduction in the pressure ratio. While comparing loss distribution between the contouring cases without fillet modification (C and S), S-type shows a reduction in total pressure loss near the hub when compared to C. This is probably due to the reduction in the strength of radial migration of flow from tipside boundary layer. Further reduction in wake strength is clearly seen for contouring case S compared to C variant. Due to intense acceleration rate near the tip, distortion of flow field from 10 to 85% span is improved resulting in more two-dimensional flow for S case. Near the tip region, S type contour shows higher losses compared to its variant with an increase in boundary layer loss. This is due to adverse pressure gradient effect from 60 to 85% of axial chord on retained low momentum fluid near the tip. Application of variable radii fillets for the above two cases, reduce the loss coefficients near the hub region. On the other hand, their application near the tip region increases the loss due to increase in the boundary layer loss.

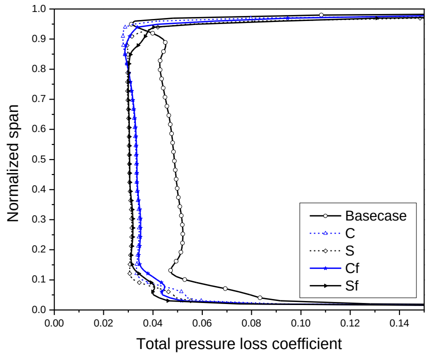


Figure 8. Spanwise distribution of Pitch averaged total pressure loss coefficient at vane exit

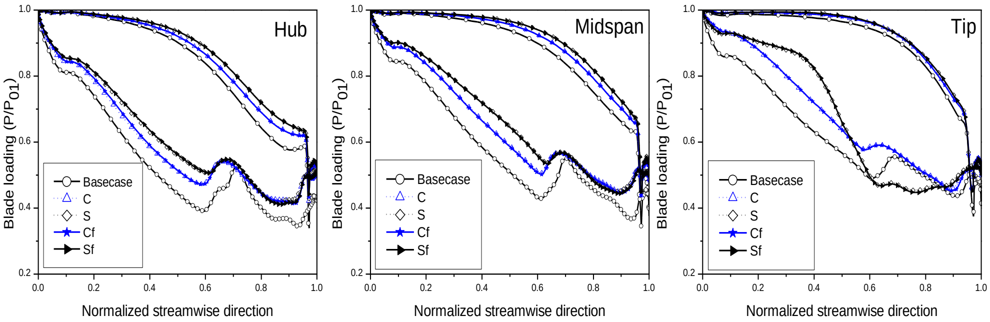


Figure 7. Blade pressure distribution along the span (a) hub (b) midspan (c) tip

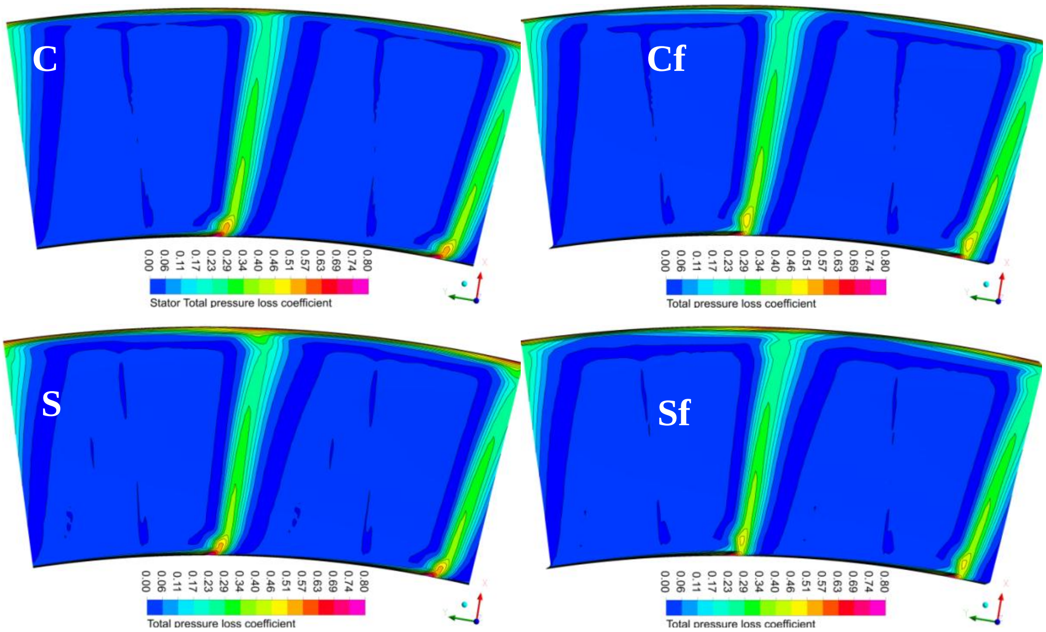


Figure 9. Total pressure loss contours at nozzle guide vane exit for different endwall contours

Figures 6 and 9 show the total pressure loss coefficient plotted at the exit of the vane for the base and contour cases. It is evident that the loss core regions are confined to wake, hub, and tip side passage vortices. With the application of tip side contours, the overall reduction in loss coefficient along the span is visible. In comparison to linear variation (C), S contour shows reduction in hub side losses but show increment near the tip side. The boundary layer loss is more due to adverse pressure gradient on low momentum fluid near the tip. Further with the application of fillets to these above contours, in hub side both cases (Cf and Sf) show improvement in hub side loss but it intensifies the losses near the tip region. Mass averaged total pressure loss at vane exit for the base cases and different contour cases are shown in table 1. Segregation of losses in each half span is also given. 29.07% improvement in total pressure loss is observed for S contour when compared to 26.5% for C contour.

Table 1. Pitch-wise averaged total pressure loss coefficient

Cases	0-50% span	50-100% span	0-100% span	% change
Basecase	0.031622	0.02537	0.05697	--
C	0.022019	0.019794	0.041884	26.5
S	0.020638	0.019650	0.040406	29.07
Cf	0.021040	0.020280	0.041369	27.38
Sf	0.019437	0.020040	0.039541	30.6

Conclusions

Numerical results are presented to consider the effect of endwall contouring combined with the leading edge modification in a highly loaded low aspect ratio transonic nozzle guide vane. Two endwall configurations having linear and S-type variation (applied at 40% -100 % of axial chord) with and without fillets are tested. Tip side contouring shows positive effects on the loss regions by reducing the transverse pressure gradient between 0-60% of axial chord and by creating low static pressure region near the tip resulting in weaker radial migration of low momentum fluid. Near hub region, S-Contour shows improvement in loss coefficient compared to C and addition of fillet further increases this trend. More two-dimensionality of flow is achieved by S contour from 10 to 85% of span due to intense acceleration compared to C. Near tip region, S contour shows an increase in loss coefficient due to growth in boundary layer compared to C case as the effect of pressure gradient on confined low momentum fluid. Further it gets worse due to addition of fillet (Sf). Overall loss coefficients are improved for both endwall contour configurations with a maximum reduction of 29.07% is realised for (S). Even though the addition of fillet increases the loss at tip side, it improves significantly near the hub region and maximum reduction 30.6% is seen for Sf contour.

Acknowledgments

Authors are grateful to Gas Turbine Research Establishment (GTRE) for financially supporting this research work.

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