The Effect of Labyrinth Seal Clearance on Stator-Well Flow and Windage Heating

ÖZTÜRK, H.K. [*], TURNER, A.B.[**], CHILDS, P.R.N.[**]

[*] Pamukkale University, Çamlık, Denizli, Turkey
[**] The University of Sussex, Falmer, Brighton, Sussex, UK

Due to heat generation arising from turbulence and viscous dissipation of energy in the boundary layer within almost any form of rotodynamic machine, the temperature rises in localised areas. Applied to rotating surfaces running in enclosed spaces, this parasitic heating is generally termed 'windage' heating and it causes the peripheral metal of the compressor drum to be heated above the usual relative total temperature. The mainstream air temperature in current high-pressure aircraft engines can reach 700^{o}C which is well above the limit of operation of titanium alloys. This mandates the use of heat resisting nickel based alloys so that the result of additional windage heating in the stator well is a weight and cost penalty.

In the high-pressure compressor, high metal temperature caused by parasitic windage heating is currently limiting the compressor design of many high-bypass-ratio aircraft gas turbines. For the next generation of large turbofan engines under consideration, the problem is likely to be exacerbated. The compression ratio and compressor delivery temperature will increase and temperatures of l00 ^{o}C above the compressor mainstream temperature could be created in the stator wells and cause thermal distortion and, possibly, catastrophic damage.

A stator-well is a shallow trench, or cavity, in the rotor directly underneath the stator blade row. The stator blades are held in interlocking shrouds in the form of a ring. This shroud ring must not obstruct the main annulus flow so the rings are recessed into this trench. The interlocking shroud that provides extra stiffness increases the blade resonant frequency and shifts it away from aerodynamic or other forcing frequencies. Since the use of shrouded blades reduces the vibration risk, the airfoils can be designed thinner than cantilevered airfoils. However, because of the pressure increase from the leading edge to the trailing edge, a leakage flow occurs underneath the stator shroud in the reverse direction to the mainstream. This leakage is usually called the stator-well flow and it can be controlled by using a labyrinth seal on the rotor between the upstream and downstream wells. The leakage flow entered radially into the downstream stator-well and is ejected from the upstream stator-well into the mainstream flow.

Although stator well leakage flow reduces the stage efficiency when it re-enters the main annulus at high angular velocity, some leakage must be accepted to remove the frictional or windage heating from the small cavities on either side of the labyrinth seal. The air in the stator well is subject to windage shear and this viscous dissipation of energy has to be carried away, or purged, by the leakage flow through the labyrinth seal. Too much flow and the compressor efficiency is penalised, too little flow and overheating can occur. The prediction of the leakage mass flow through the stator-well labyrinth seal is thus of crucial importance. In order to calculate the leakage flow rate, a precise knowledge of the seal clearance and the metal temperatures is required. The calculation of the optimum leakage flow is an important one since it trades disc metal temperature for compressor aerodynamic efficiency. It is now known that shallow stator-wells are better than deep stator-wells at reducing windage heating.

The structure of the leakage flow through the stator-wells is not known with any certainty. There have been few experimental investigations published on this topic owing to the difficulty, complexity and cost of experimental rigs and none have been reported in which the flow velocity has been measured or in which the structure has been observed.

The flow in a compressor stator-well to be divided into three regimes. The first regime represents the 'artificial' condition. For this regime, the labyrinth clearance is considered as zero so no leakage would occur from the downstream stator-well to the upstream stator-well. If there is no pressure gradient across the stator blade, the same regime may be seen. The second regime illustrates the common situation whereby there is some leakage through the labyrinth seal with both ingress and egress occurring at the downstream and upstream well peripheral seal. For the third regime, due to the pressure gradient between downstream and upstream well, the throughflow of air suppresses any egress of flow at the downstream peripheral seal. For this case, the labyrinth seal radial clearance is large enough to allow leakage flow.

if the labyrinth clearance is decreased, the pressure in the downstream well radially increased. If the pressure is high at the downstream gap region, since the pressure gradient will be small between the inside of the downstream well and traling edge of the stator blade rows, the ingress flow into the downstream cavity will be decreased. It is well known that the reason for the leakage from downstream cavity to upstream cavity due to the pressure difference between the inlet and outlet of the radial labyrinth seal. When a high pressure area exists at the inlet of the labyrinth seal, it pushes more flow through the labyrinth seal Therefore, in order to decrease the leakage, a low pressure region should be created at the inlet of the radial labyrinth.

It has been noted that the tangential velocities increase by decreasing the labyrinth seal clearance in the upstream stator-well. Tangential velocity variation in the upstream well show the same features as the downstream well. For the downstream well tangential velocity, the same profile has been reported. The variation of the radial velocity in the upstream well was not the same with the downstream well radial velocity profile. When the labyrinth clearance is decreased, the radial velocity in the upstream well increases. It may be argued that when the leakage decreases, the flow may be speeded up easily in the upstream well.

When the labyrinth clearance decreases, the tangential velocity increases in the both upstream and downstream wells. This supports the idea of a relationship between the tangential velocity and leakage rate for the stator-well. Another relationship can be considered between the tangential and radial velocities. It has been noted that when the tangential velocity increases, radial velocity increases, too.

Although leakage flow may be reduced by decreasing the labyrinth seal clearance, generally, it is not possible to use a small labyrinth clearance because it causes rubs between the stationary and rotating surface and the possibility of catastrophic damage. One of the objectives of this study is to show a new approach to decreasing the leakage without reducing the labyrinth clearance.

One of the ways to control the leakage flow is to change the labyrinth seal clearance. Reducing the seal clearance decreases the flow rate but increases the windage heating. It is therefore important to know the effect of seal clearance on the leakage flow for designing efficient aero-engine compressors. In general, the radial clearance between the rotating and stationary surfaces should not be decreased below some critical value, due to the probability of ‘rubs’ which can occur in rapid engine transients and cause catastrophic damage. Also, these ‘rubs’ can cause overheating and affect the life of the whole disc assembly. The aim of this paper is to show effect of labyrinth seal clearance on stator well flow and windage heating.