

A significant level of development in the area of aviation sealing technology has occurred in recent years. Professor Sir David King, Dr Oliver Inderwildi and Dr Chris Carey of the Smith School of Enterprise and the Environment look at the advantages that new sealing technology can offer in order to reduce aviation's environmental impact.

Sealing technologies – signed, sealed and delivering emissions savings

Sealing in the energy

As gas turbines are the main source of propulsion in aviation, developments which improve them can produce a significant reduction in fuel consumption and consequently in CO₂ emissions. Hence, aviation's impact on the environment can be mitigated by advances in turbine technology.

Gas turbines work by manipulating the flow of gas which is central to the efficiency of the system. Gas path sealing is therefore a fundamental area of interest when seeking improvements in the efficiency and performance of aircraft. By reducing the level of leakage from the gasflow, efficient sealing helps

retain the energy introduced to the gas stream. Leakage occurs in a number of areas and is both accidental, such as between pressure stages, and intended, for example secondary air systems. These secondary airflow systems include internal engine cooling flows, external bleed air for accessories and

cabin feed as well as unwanted leakage. Reducing secondary flow by precise control has the potential to result in a four to six per cent increase in power and a reduction in specific fuel consumption (SFC) by between three and five per cent. There are a number of key sealing locations in gas turbines: the fan and compressor shroud, the compressor interstage and discharge seals, the turbine interstage and bearing seal locations.

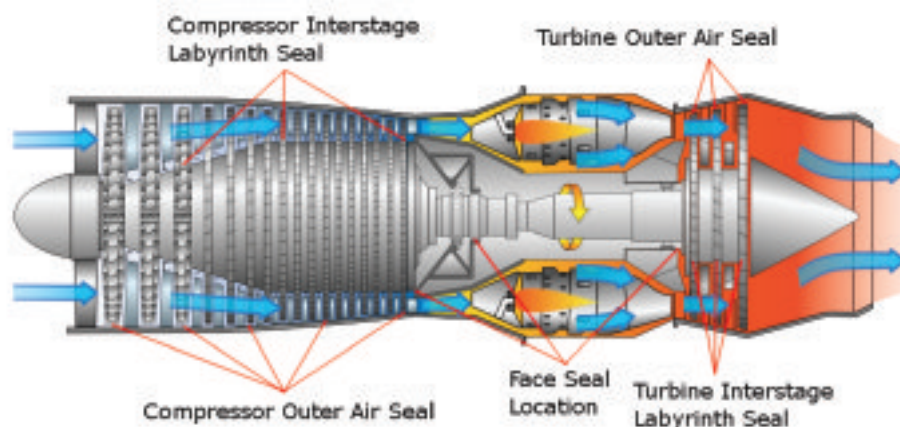


Figure 1: schematic of approximate seal locations and example sealing technologies in turbine engines.

Keepin' it tight!

Applicable seal technology depends on the location which requires sealing. *Figure 1* indicates examples of seal locations and the types of seals currently used. The following section identifies current technology used as well as future techniques which could reduce leakage rates for outer air seals and inter stage locations.

Outer air seals

Outer air seals are located between the tip of the blades and the casing or shroud and are used to seal the cavity over the rotating blade. The environmental conditions at the tip seal location are harsh, reaching temperatures in excess of 1,400°C, pressures over 4,000 kPa, and high surface speeds over 600 ms⁻¹. The presence of unburnt fuel and ingested debris, such as sand, complicates the sealing process, as do changes in part dimensions due to mechanical and thermal loading. This causes a variation in the clearance or gap between the blade tip and shroud.

However, as engines age and turbine blades become worn, the clearance between blade and shroud can increase up to 50mm, leading to a loss of thrust. To overcome this, an increased throttle setting is required which increases fuel use. For each 1mm of additional blade tip clearance, fuel use increases by one per cent. The increased distance between the blade tip and the shroud accounts for between 80 and 90 per cent of engine performance degradation.

Abradable seals

The current method of sealing used at the outer air seal location is abradable coatings on the shroud. Materials used for this are dependent on the temperature of the location. Low temperature locations, such as fan tip sealing, use epoxy systems. High temperature locations, such as turbine blade tip sealing, use porous ceramics. The coating allows for rubbing of the shroud by the blades during service, whilst providing the minimum clearance. Without abradable shrouds the clearances when the engine is cold

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must be large enough to ensure blade rub does not occur. The surface must also remain smooth to reduce aerodynamic losses. Seals come in three main types, abradable (sintered or sprayed porous material), compliant (a porous material that compacts on blade rub), or low shear strength (sprayed aluminium).

Advanced sealing techniques

A number of methods are being investigated to reduce blade tip clearance. The two main ways of altering this are the use of actuation and regeneration of the abradable seal. Both techniques can be identified by the control architecture used and the method of actuation. The method of control can be either active, where an external control method is used, such as sensors, or passive where the environment within the turbine, such as the temperature, induces the necessary response from the system. The method of actuation can be mechanical, thermal or pneumatic.

Thermal actuation

Active thermal control is the use of selective cooling of the turbine case during operation, resulting in a reduction in blade tip clearance. A number of commercial engines, such as PW4000 and GEnx (see *figure 2*), use this method. Thermal systems are relatively slow and cannot be used during transient events, such as take-

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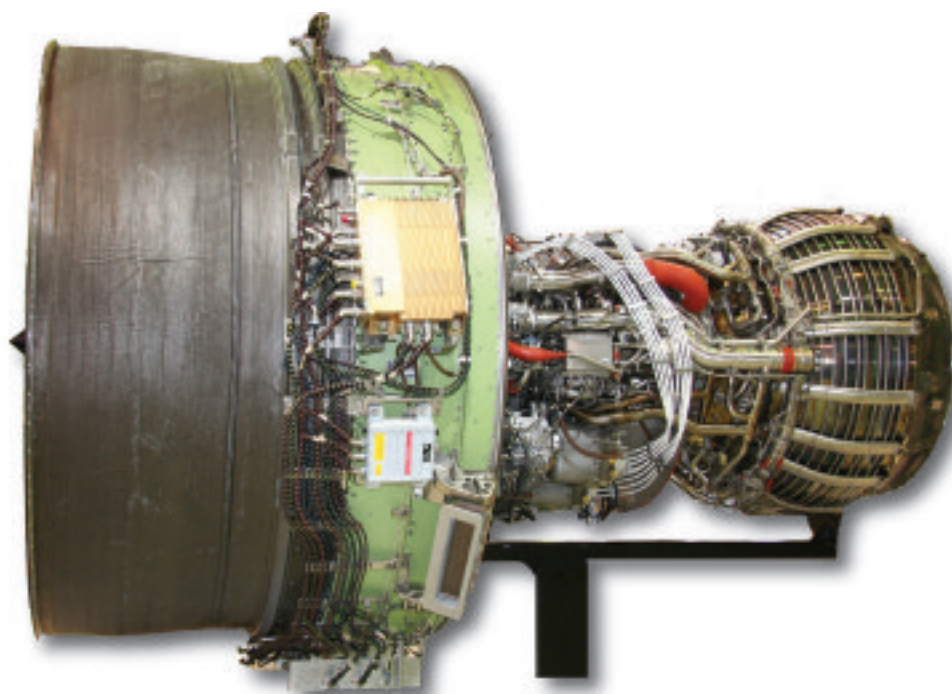


Figure 2: GEnx engine illustrating thermal tip clearance control mechanism on turbine stage.

off and reacceleration and are therefore only usually used at cruise conditions. The main area of development in these systems is in producing thermally efficient materials which could provide a more responsive system. Faster response of the system would allow the use of tip clearance control throughout the mission, rather than just at cruise. Passive thermal control uses the material properties and engine operating temperature to alter the blade tip clearance. The stators (fixed turbine blades which re-align the airflow after a rotor stage) consist of a combination of materials with varying coefficients of thermal expansion. This means that different parts of the engine contract and expand at differing rates without external control inputs. While accurate and reliable, active thermal systems only provide optimum clearance for the minimum clearance conditions, such as take off and manoeuvring. They do not capitalise on the longer stabilised cruise conditions of the flight profile meaning the overall benefits for a given flight plan are minimal. Passive thermal systems are not currently in use in any system.

Mechanical actuation

As mechanical actuation relies on a mechanical movement to vary the tip clearance it doesn't lend itself to passive control. Motive power required to close the gap is supplied by hydraulic, electromagnetic and magnetic systems. The significant challenge specific to this methodology is the development of actuation systems which can withstand the harsh environment of a gas turbine. In addition, secondary sealing systems for the moveable shroud and the weight and the complexity of the necessary mechanisms involved are of concern. One way of bypassing some of these problems is the use of shape memory alloy (SMA) actuators. Initial studies by NASA into SMA compressor case compensator rings show that copper-aluminium-nickel actuator rings can reduce the blade tip clearance from 5mm to 1mm. Calculations suggest that the full application of this technique through the axial compressor could increase engine efficiency by 0.7 per cent but would require a high temperature SMA. Current indications are that SMA actuators will find their way into the next generation of turbine engine providing the reliability criteria are met.

Pneumatic actuation

Active pneumatic systems use the pressure generated by the compressor stage to move sealed shroud sections to reduce the blade tip clearance. These systems are very sensitive to pressure balancing and suffer from high cycle fatigue. They also require a great deal of system pressure which reduces the overall efficiency of the turbine, reducing the efficiency increase provided by the gap reduction.

Passive pneumatic systems are driven by engine-generated gas pressures or hydrodynamic effects. They cover concepts such as floating shroud segments and blade tip cooling air discharge. They rely on a very limited blade tip area, extremely accurate positioning, tight alignment tolerances, friction levels and secondary seal hang-up that make these systems very unattractive to engine manufacturers. The flexible bellows which deflect the shroud are also subject to high cycle fatigue. Pneumatic actuation will have to overcome several problems before it can be considered for in-flight use.

Regeneration

Other systems use a rub-avoidance methodology, but regeneration systems aim to regenerate or restore the tip seal. They can be either passive or active in control and produce regeneration of the seal where it has been abraded by blade contact. An example of a restoration concept is mechanical restoration where ground crew can alter the clearances through the use of linkages. The disadvantage of this is the additional weight and volume due to the mechanical systems as well as the accessibility of the mechanism for routine adjustment by ground crew.

Regeneration of the seal uses specially engineered material systems that undergo growth because of thermal, chemical or electrical interactions. They remove the requirement for secondary sealing and can use the environment for passive control, reducing the complexity of the system and therefore the overall weight. They can be actively controlled by using chemical reactions that are progressed or retarded by electrical stimulus.

Problems with these systems include uniformity of growth, strength of grown material and growth rate, as well as excessive blade-tip wear caused by the constant abrasion.

reducing the thermal expansion effects on the clearance of the seal. These savings relate to a 1.8 per cent increase in power and a 1.3 per cent increase in efficiency.

includes cobalt based super-alloys which can withstand temperatures of up to 700°C and rotational speeds of 300 ms⁻¹. In order to meet the demands of advance engine designs, nickel-based

Interstage locations

The current technology of these locations is mainly labyrinth type seals. Developments in this area are significant and varied due to the number of locations within the engine with individual demands. Advanced seals will generally be expected to operate in higher temperature environments, with greater pressures across the seal, in order to accommodate higher pressure ratios as well as operating at higher speeds.

Labyrinth seals

Labyrinth seals are the most common flow path seals applied to turbine engines. They consist of several knife edges, typically five, in close clearance (0.25 to 0.50mm) in a number of configurations (*figure 3*). Labyrinth seals rely on controlled leakage across the seal. This is driven by the pressure differential between the seal ends. The design of the seal forces the flow to separate at the knife edge causing a loss of kinetic energy and pressure from the gas flow. This is repeated in the next cell and so on until the gas leakage reaches the seal exit. Current labyrinth seal applications can withstand temperatures as high as 700°C and pressure differences of up to 3,000 KPa.

However, vibration of the shaft can cause the blades to bite or rub into the shroud, increasing the flow between cells and reducing the sealing efficiency. Current advances in labyrinth seals focus on the use of abrasive knives and sacrificial ceramic shrouds to reduce leakage rates while allowing for rubbing to occur. The use of sacrificial abrasive layers results in a reduction of the running clearance by 90 per cent, allowing for an overall improvement in engine efficiency by one per cent. The ceramic coating also reduces the underlying metals' temperature by 20 per cent and thermal displacement by 34 per cent. This has the effect of

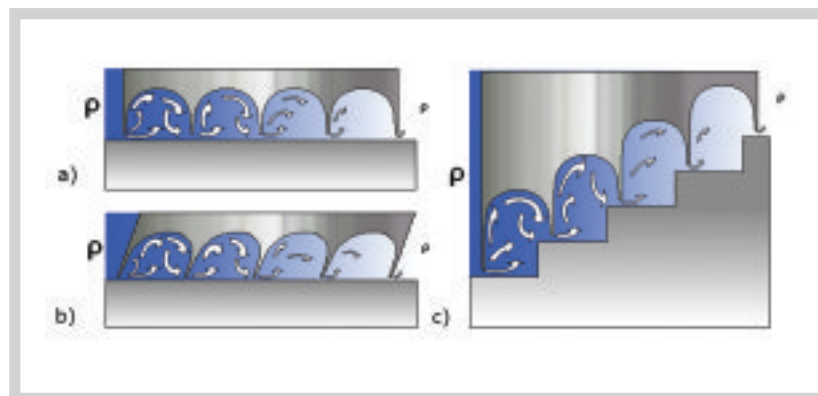


Figure 3: examples of labyrinth seal configuration a) straight, b) angled, and c) stepped.

Brush seals

Brush seals consist of a dense pack of bristles sandwiched between a face and backing plate (*figure 4*). A significant benefit of brush seals over labyrinth seals is the ability to accommodate movement of the shaft and return to small running clearances. It has been reported that brush seals have 5-10 per cent the leakage rates of similar labyrinth seals with a 34 per cent reduction in footprint.

However, they can still be subject to catastrophic wear at the brush-shaft interface due to excessive thermal loading. The clearance, and therefore leakage, rates of brush seals are related to the rotational velocity of the shaft. As at high velocities, hydrodynamic forces can push the bristles away from the shaft. Bristles material currently

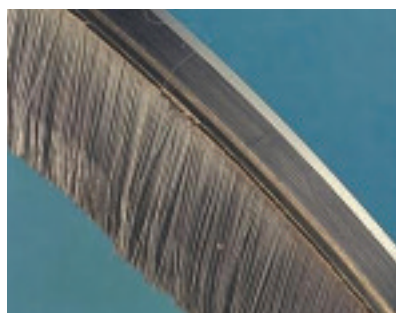


Figure 4: detail of brush seal.

super alloy will be used to allow maximum working parameters of 800°C and 600 ms⁻¹.

Developments of brush seals include shoed brush seal, where pads are spot welded on to the end of the brushes, giving a closer and more consistent face to reduce leakage rate further. Other advancements in brush seals include hybrid brush seals which are an effort to reduce brush wear, and the use of ceramic fibres, such as silicon carbide and aluminium oxide, to reduce fibre wear.

The stiffness of the wire limits the pressure differential across brush seals, which is currently 670 kPa per stage. New stiffer bristle materials such as ceramic and super alloys will increase this value to approximately 950 kPa per stage. Leaf seals overcome this by replacing the bristle with plates, with greater axial strength. This allows a larger pressure differential across the seal. Laminar leakage between plates is low and hydrodynamic lift prevents contact on operation thus reducing wear. A 66 per cent reduction in leakage rates has been reported compared to labyrinth seals. Another variation of this is the wafer seal which differs in the root attachment method and moment of inertia but operates on the same principles.

Film riding or foil seals

Film riding seals consist of thin foil metal fingers, sometimes spring loaded, which are designed to operate without contacting the shaft by the use of hydrodynamic forces (*figure 5*). This greatly increases seal life, keeping the engine within performance characteristics for longer resulting in better fuel economy. These seals can withstand higher pressures (5,500 kPa) and temperatures (800°C) than other sealing methods. When compared with labyrinth seals, a 66 per cent reduction in leakage has been reported for film riding seals. While most designs are face seals, some turbine rim seal applications have also been suggested as possible. Problems with this type of seal include dust ingestion and aircraft manoeuvring loads which can cause contact between seal faces.

Finger seals

Finger seals consist of multiple fingers or flexural elements aligned around the circumference of the shaft (*figure 6*). The finger acts as a cantilever allowing radial movement of the seal face and movement of the rotor. The seals are applied in offset groups, reducing the leakage through the fingers. Finger seals are designed to move radially inward, towards the rotor when pressure differentials develop. Initial studies show that these seals have a longer average life than brush seals, with 60-70 per cent of the flow factor.



Figure 6: detail of finger seals showing offset.

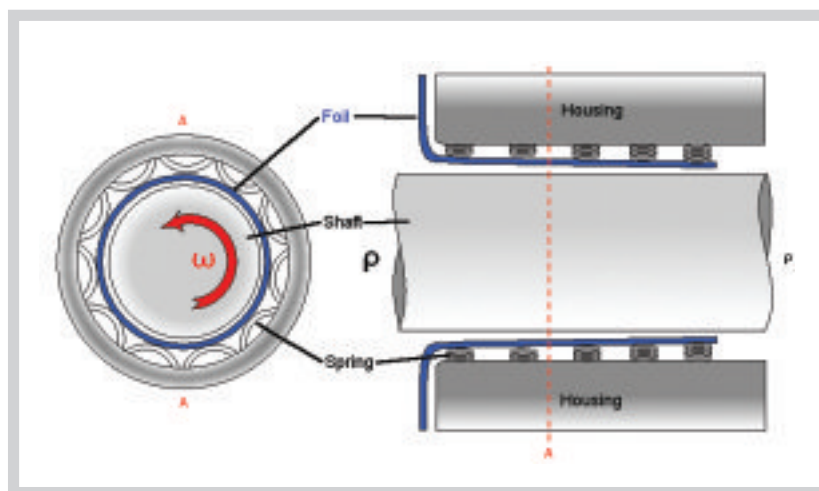


Figure 5: foil seal schematic.

Conclusion Outer air seals

The degradation of outer air seals is a significant factor in the reduction of engine performance. While abrasible shrouds and thermal contraction of turbine casing have increased efficiency, improvements so far are limited and are hindered by slow reaction times and a lack of suitable measurement systems. Using any of the systems discussed here to reduce the blade tip clearance by 1mm results in a one per cent saving in SFC. With U.S. aviation expected to use approximately 19 billion gallons of aviation fuel in 2009, this equates to a saving of 200 million gallons of fuel, and subsequent savings in emissions, at a cost saving of nearly \$400m in one year in the U.S. alone at current prices. Another issue is the development of measuring techniques which can work reliably in the extreme environments within jet turbines.

There are a number of significant developments in the pipeline in the area of gas flow sealing and when applied, either in full or in part in the next generation of turbine engines, they will help manufacturers reach the challenging targets for fuel-burn reduction, thrust increase and increased service life.

Interstage seals

The benefits of advanced seal technology are significant. Studies on an AE3007, a modern 40kN thrust regional engine, showed a reduction in

SFC (1.96 per cent) and increase in thrust (4.93 per cent) by implementing brush seals at two turbine interstage locations. The use of more advanced film riding seals in place of the brush seals resulted in a 2.62 per cent reduction in SFC and a 6.95 per cent increase in thrust.

The applications of low leakage film-riding seals can reduce the cycle air used to purge high pressure turbine cavities by 50 per cent. This saving in volume of airflow can be used to hold the rotor inlet temperature constant allowing for a SFC drop of 0.9 per cent, a thrust increase of 2.5 per cent or a mission fuel burn drop of 1.3 per cent. This 0.9 per cent drop in SFC could result in a saving of more than 500kg of fuel per hour on a CF6 80C2-B1F-powered 747, equating to nearly 40 tonnes over a 75,000 hour life of an aircraft.

Another benefit of advanced sealing technologies is the ability to increase the pressure ratio of turbines. Increasing the pressure ratio results in more of the thermal energy being converted to jet speed, thus increasing the engines' efficiency and lowering the SFC. However, increasing the pressure ratio causes a greater strain on the components involved, with seals being the weaker link in the chain. Increasing engine pressure ratios has been shown to cause a decrease in overall engine weight. Advancements in seal technology can be made with much smaller investments; 20-25 per cent of development costs for compressor or turbine developments.