FOIL FACE SEAL TESTING

John Munson
Rolls-Royce
Indianapolis, Indiana

Seal Development Strategy

- Foil thrust bearing provides a compliant primary (stationary) seal ring
  - Gas film stiffness is greater than primary ring structural stiffness - accommodates the out-of-flat distortion
  - Provides greater tolerance to wear and contamination in the air stream - no fine geometry or small holes needed
- Combining foil thrust bearing technology with face seal architecture - secondary seal accommodates axial excursion and some angular misalignment
- Foil bearing need only support itself axially, modest load capacity required
- An extension of existing technology

Rolls-Royce

In the seal literature you can find many attempts by various researchers to adapt film riding seals to the gas turbine engine. None have been successful, potential distortion of the sealing faces is the primary reason. There is a film riding device that does accommodate distortion and is in service in aircraft applications, namely the foil bearing. More specifically a foil thrust bearing. These are not intended to be seals, and they do not accommodate large axial movement between shaft & static structure.

By combining the 2 a unique type of face seal has been created. It functions like a normal face seal. The foil thrust bearing replaces the normal primary sealing surface. The compliance of the foil bearing allows the foils to track distortion of the mating seal ring.

The foil seal has several perceived advantages over existing hydrodynamic designs, enumerated in the chart. Materials and design methodology needed for this application already exist. Also the load capacity requirements for the foil bearing are low since it only needs to support itself and overcome friction forces at the anti-rotation keys.

3

Face Seal Test Results

- **Seal lift-off**
  - **Inversely proportional to square root of load**
  - **Protective coatings required for foils**
- **Radial coning - allowable coning only limited by the amount of clearance provided by bump foils**
- **Circumferential out of flatness**
  - **Up to 0.009 in./4 wavelengths static side out-of-flat**
  - **Also rotating mating ring machined out-of-flat:**
    - **Max requirement 0.008 in. - ~➢16” seal**
    - **Scaled for ➢4.5 in. seal - 0.003 in. - preserves wave aspect ratio**
    - **1, 3, & 5 wavelengths successfully tested**

Rolls-Royce

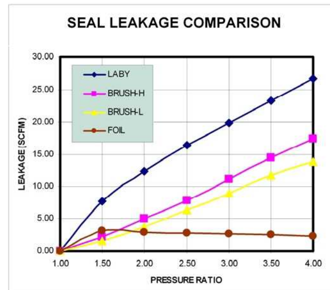
Lift-off testing was done to establish where would we expect an engine seal to go from contacting to non-contacting. Extrapolation of the test results indicates that this should occur between 1500 and 2000 RPM. While this is well below the engine operating range, it implies that some form of protective coating is required for the foils.

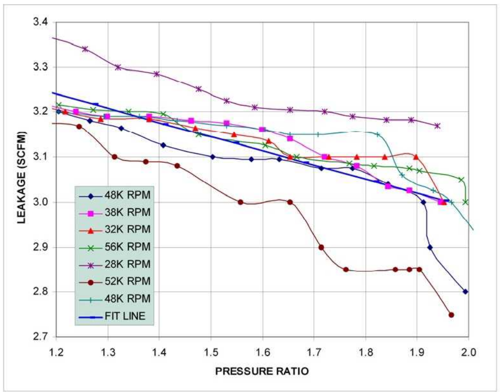
The seal was tested with up to 3° of coning built into the mating ring. The test results seem to suggest that the only limit to how much coning the seal can accommodate is a function of the clearance built into the bump foil. No difference in operation was noted between coned and non-coned mating ring tests.

We also presented results wherein the static structure was made out-of-flat circumferentially. The seal easily accommodated 0.009” of distortion. These results were supplemented with additional testing wherein the rotating sealing surface was manufactured circumferentially out-of-flat (OOF). The goal 0.008” OOF requirement was scaled for these tests to preserve the aspect ratio of the “wave.” A maximum of 0.003” OOF was used for the 3 and 5 wavelength tests. With 5 waves the OOF is equivalent to 0.009” OOF with a 16” diameter seal. The seal also accommodated this distortion, although with 5 waves, 0.003” OOF load capacity was reduced by approximately 30%.

4

Prototype Seal Test Demo: Leakage Results





Rolls-Royce

The proof-of-concept seal was also used to characterize expected seal leakage so that this seal could be compared with other types of seals, e.g. labyrinth or brush, used in secondary flow path applications. Tests were run with a variety of axial loads and differential pressures applied. The tests were conducted at several different speeds, as well. As the figure indicates, no clear effect of speed on leakage was observed. A general leakage curve was fitted to the test data. This curve was used to compare foil seal leakage to other seals. This result is shown in the figure at top right. At very low differential pressures the seal s all give similar performance. At higher differential pressures the foil seal is clearly superior.

5

Present Requirements

- Large diameter seals, up to 36” diameter
  - Require large axial motion capability ±0.2”
  - Up to 1200°F
  - <100 psid
  - 1000 ft/sec
- Prototype seal test article ~1/7 required size
- Current test article ~1/2 size
  - Fits in available test rig
  - Large enough to develop full speed, pressure, temp test conditions
  - Test for any size effects as technology gets scaled up

Rolls-Royce

In terms of cost versus benefit it has always been clear that there are only certain engine sealing locations where the foil type face seal is best suited. These are “high-value” sealing locations within engines such as rotor thrust balance and/or turbine rim seals. As encouraging as the proof-of-concept testing was, it is a long way from the small 4.5” OD demo seal to the up to 36” diameter seals that will be required for the applications under consideration.

As the slide shows, temperatures and speeds tend to be high but differential pressures modest relative to all other seal industry applications. Some of the applications under consideration will also need to accommodate large axial excursions. Radial excursions are also equally large. These have not been shown because they can be easily accommodated by ensuring the mating ring face is always large enough so that the primary sealing face stays completely in contact with the mating ring. For a conventional spiral groove type film riding face seal these excursions would be more concerning as they would have led to unsymmetrical lift forces.

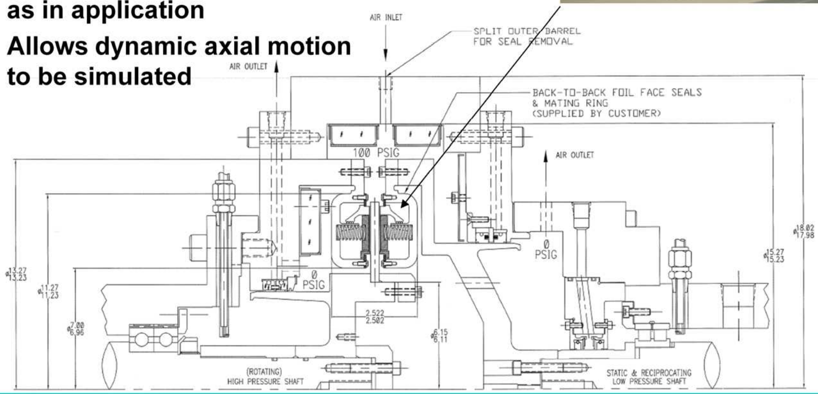
Present plans are to test an approximately half size seal. This size was selected because:

- It provides a means to check for effect of size on seal performance
- To allow supplier supply chain development for large parts
- Test rig size limitations versus the type of testing desired

6

Test Rig Configuration

- **Face-to-face seal configuration**
  - **Concession to rig: OD pressurization instead of ID as in application**
  - **Allows dynamic axial motion to be simulated**



Rolls-Royce

The ability to simulate the expected axial excursions while the seal was rotating was seen as a prime requirement for selection of a test rig. This and the envisioned size of the test parts determined the selection of the test rig. Stein Seal's dual shaft rig is being configured to run the planned test program. Two test seals are used in a face to face configuration to eliminate the large thrust imbalance load that a single seal would have imposed on the shaft.

The completed test seals are shown in the small upper right hand figure. The seals are right and left handed but otherwise identical in design.

Planned Test Program

- Performance mapping
- Dynamic axial motion – 10 sec slow transient (thermal growth)
- Distorted Mating Ring
  - (1) Coning (0.5° radial) – Thermal/pressure induced (usually)
  - (2) Swash (.002” TIR) – mounting errors
  - (3) Circumferential out-of-flat (.001” peak to peak)
  - (4) Combination of 2&3
- Dynamic axial – <0.1 sec, fast transient (compressor surge)
- Dust ingestion (10μm, .0003 Lb_m/sec)
- Windmilling both directions

Rolls-Royce