Brush Seal Hysteresis

Pete Crudgington [1], Aaron Bowsher.[2] And Tracey Kirk[3]
Cross Manufacturing Co. (1938) Ltd., Devizes, England

Jas Walia[4]
Product Development Services., Solihull, England

The use of Brush Seals continues to expand in both the Power Generation and the Aerospace markets and we continue to learn more about their functionality. This paper continues on from our previous papers and in particular AIAA 2002-3794 which examines, analytically and experimentally the effects of Hysteresis. The 3D Finite Element Model has been developed further to more accurately predict the physics of brush seal hysteresis. This will be demonstrated by comparison of data from the model to test data gathered from manufactured seals tested in the laboratory. This model has full bristle-to-bristle contact, bristle to back plate contact, bristle to rotor contact and can be pressure drop loaded.

Nomenclature

β_F : inertia factor
μ : dynamic viscosity
ρ : density
$\mathbf{E}$: axis vector
$\mathbf{f}^B$: body force per unit volume
i, j : axis directions
K : permeability
p : pressure
$\mathbf{V}$: velocity

I. Introduction

Cross have been manufacturing and developing brush seals since the 1970's. With many successful applications now present in both aerospace and ground running turbines. The understanding of the behavior of the brush seal in service has expanded greatly over the years.

Early test programs in the 1980's (1) uncovered the phenomenon commonly referred to as hysteresis. This is when the leakage through a seal increases after a radial closure event. The bristles get pushed back during the closure and do not fully recover after the event, once the pressure is removed from the seal the bristles do however fully recover and the seal will perform to the same level as before the radial closure.

This paper describes a full 3D Finite Element Analysis model of a bristle pack with pressure distribution data added from a porous media CFD model and the results compared to test data. The work is a continuation of details presented in our 2002 paper (2) that traced the development of the FEA model from a simple beam element model through to the complex multi row, multi layer 3D model we have today.

---

[1] Manager, Brush Seal and Aerospace Products, Hopton Rd, Devizes, England, AIAA Senior Member.
[2] Engineering Manager, Brush Seal and Aerospace Products, Hopton Rd, Devizes, England,.
[3] Test & Development Engineer, Hopton Rd, Devizes, England.
[4] Managing Director, 80 Sharmans Cross Rd, Solihull, England.

II. Hysteresis

Hysteresis is defined as "*the lagging behind of an effect when its cause varies in amount*". In the case of a brush seal the hysteresis is a friction dominated phenomenon caused by bristle to bristle friction and bristle to back plate friction. The phenomenon can be seen in simple stiffness checking tests(2) with no pressure drop across the seal and during transient running with pressure drops across the seal. In this situation the leakage through a seal increases after a radial closure event. The bristles get pushed back during the closure and do not fully recover after the event. Once the pressure is removed from the seal the bristles do however fully recover and the seal will perform to the same level as before the radial closure.

The hysteresis under pressure can be varied by detail design of the seal, the bristle angle effects this as does the style of back plate used. A number of patents (3&4) have been granted that cover back plate features that are aimed at pressure balancing the bristle pack and thus reducing the level of hysteresis that a seal exhibits.

Graphs illustrating both types of hysteresis are shown in Figures 1 and 2.

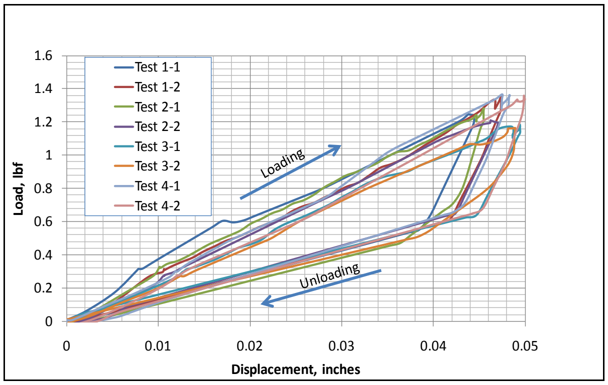

Figure 1 Stiffness Checking Hysteresis

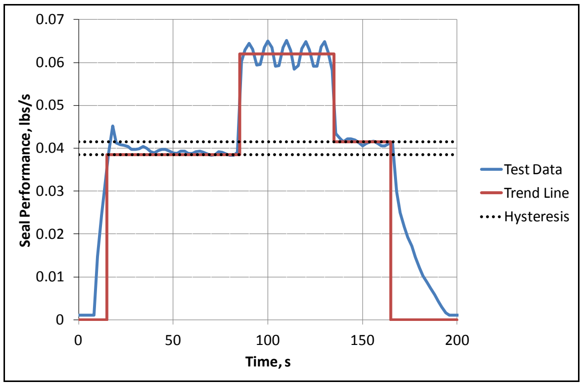

Figure 2 Hysteresis with .010" Radial Offsets

III. Computational Analysis

The computational tool that has been used for all the analysis performed todate by Cross has been the commercial code ADINA. Cross first presented basic beam element model details in 2001 (5). The model expanded rapidly and in our 2002 work(2) we presented details of how the models had evolved. Starting with simple single beam element models we moved onto single layer multi row 3D models and then onto multi layer multi row 3D models. In our 2009 work (6) we showed how the model had evolved further with the correct end treatment of each bristle and with more layers available in the analysis it was becoming significantly closer to physical brush seals.

A. FEA Model

Most recent work on the FEA model has been to simplify the input process. The models are now fully parametric you simply input the wire diameter, the length, the angle, the number of layers, the coefficients of friction, the axial spacing between layers, the circumferential spacing between rows and the axial and circumferential flare parameters. The model then creates all the geometry using alternating layers of 4 and 5 bristles, this is shown below in Figure 3 for a 12 layer model that contains 52560 nodes.

As previously the model is a full 3D model, it utilizes the cyclic boundary conditions available in Adina. It has 3D contact between all bristles, contact between the last layer of bristles and the back plate and contact between the bristle tips and the simulated rotor, with different values of the coefficient of friction specified at each.

With no further boundary conditions the model can be used to simulate the typical stiffness checking tests. Results from this for two seals are shown later in the paper in section IV and compared to test data.

In order to accurately simulate situations in which a pressure drop is present, more boundary conditions are needed. The pressure distribution down the back plate and the pressure distribution through the bristle pack are needed. Some of this data can be hard to gather in enough points experimentally so we set about obtaining it analytically.

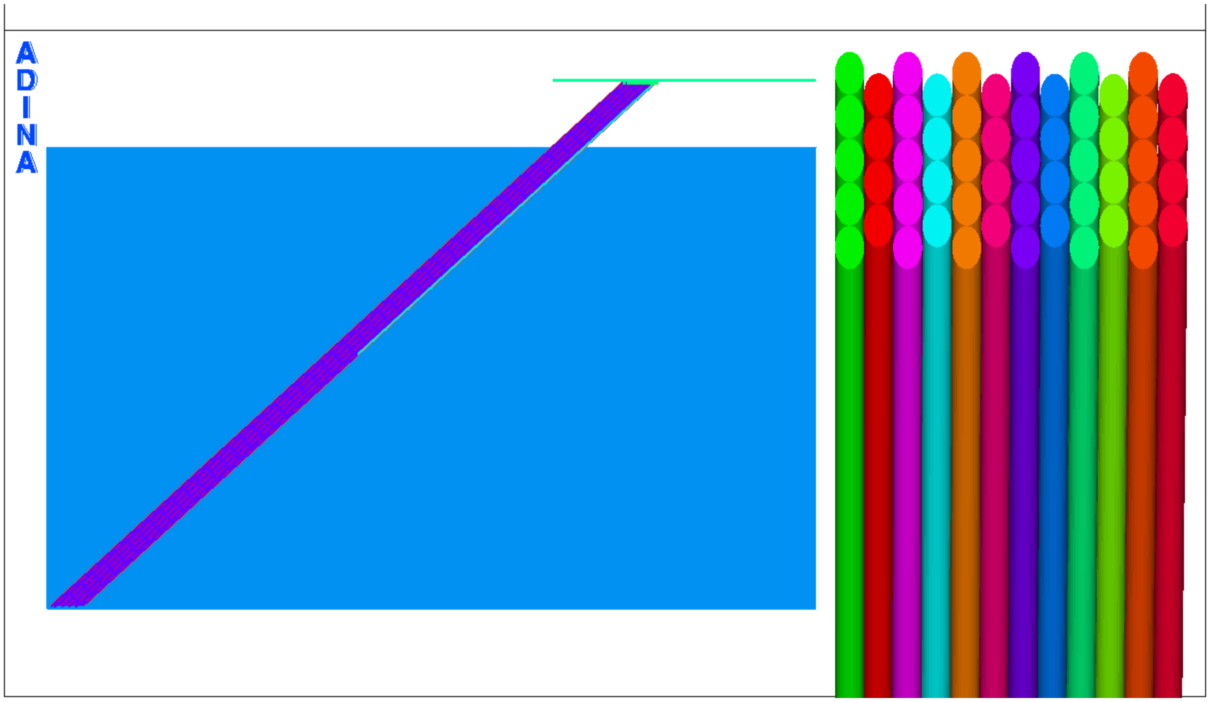

Figure 3 12 Layer FEA Model.

B. CFD Model

As stated above the CFD model was needed to get enough accurate data to correctly assign the boundary conditions to the FEA model. We reviewed published work in this field(7, 8, 9, 10, 11, 12 & 13) and decided that rather than modify our 3D bristle model it would be easier at first to create a porous flow model of the bristle pack. Jas Walia, from Product Development Services the UK agents for Adina created the parametric model along similar lines to other work. We did however enhance the model by creating a more porous zone that is half the thickness of the last layer of bristles, in real seals this area is more porous as the bristles here are pushed up against the back plate rather than more bristles. We also created areas on the back plate that would enable us to model the effects of creating pockets here and pressure balancing the brush seal. These areas are easy to turn on and off so we could look at standard and pressure balanced brush seals with ease. The 2D axisymetric model, with no slip boundary conditions at the wall has a total of 37901 nodes.

Defined permeable and inertial factors are utilised to characterise the flow through the bristle pack. The flow through the bristle pack is assumed to be anisotropic and therefore differential factors are used for the different principal axis. The general form that governs the flow through porous media can be expressed as follows(14):

$$\beta_F \rho \| \mathbf{v} \| \mathbf{v} + \mu \mathbf{K}^{-1} \cdot \mathbf{v} = - \nabla p + \mathbf{f}^B$$

where $\mathbf{K} = K_{ij} \mathbf{E}_i \mathbf{E}_j$

is the permeability tensor and β_F is the inertia factor

The model is shown in Figure 4, the pressure distribution obtained is shown in Figure 5

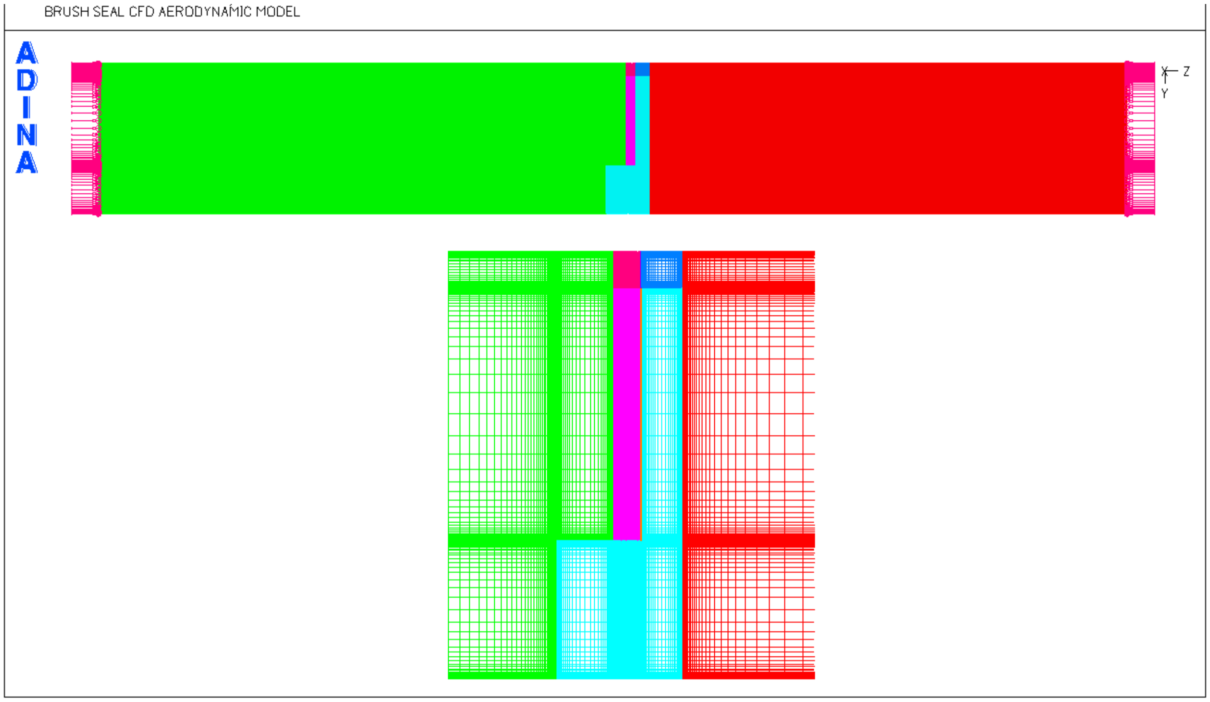

Figure 4 Brush Seal CFD Model

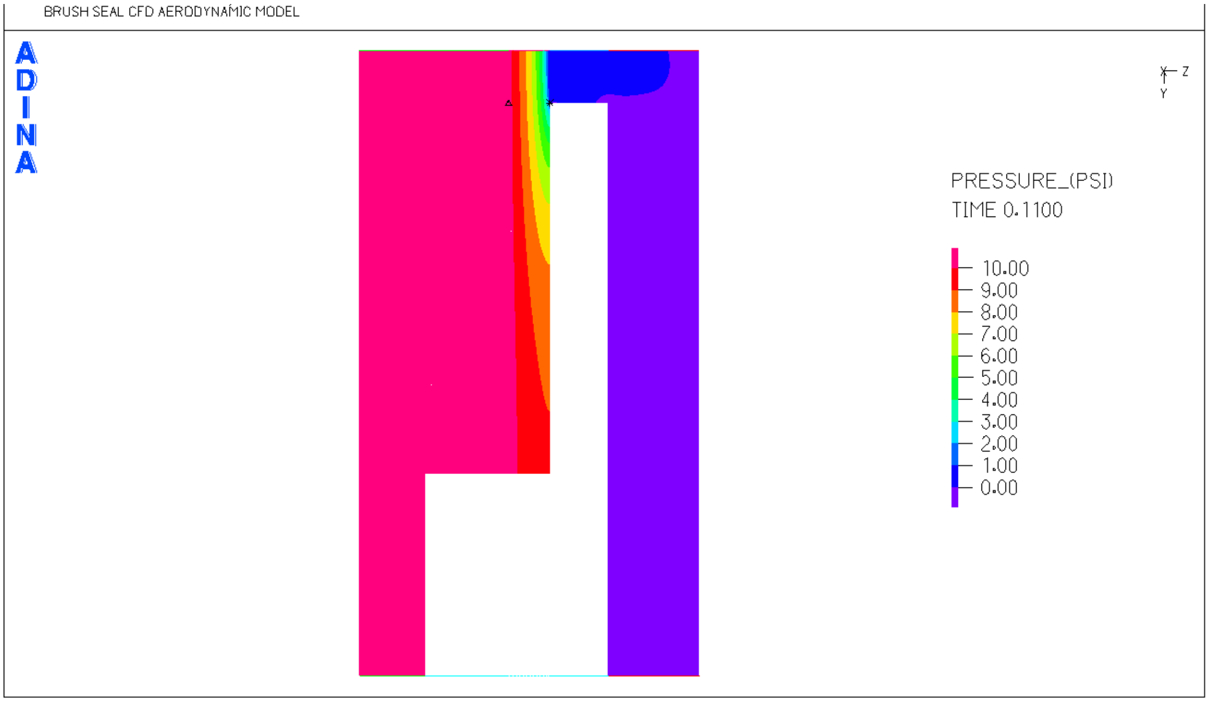

Figure 5 Brush Seal Pressure Distribution

C. Verification of CFD Model

In order to verify that the CFD model was giving realistic data it was decided to run some static tests at Cross and measure the backplate pressures at 3 radial locations on 2 brush seals. The seals chosen were different in design, one was pressure balanced with a pocketed back plate design, the other a conventional brush seal. Photos of the test set up are shown in Figure 6. Basic design parameters for the two seals are shown in Table 1.

Table 1 Seal Geometry

Seal	Bristle Bore	Bristle Diameter	Bristle Density	Bristle Angle	Front Plate Bore	Bristle Free Length	Stiffness	Pressure Balanced
#	Inches	Inches	Wires/Inch of Circ	Degrees	Inches	Inches	lbs/inch	
Seal A	5.0982	0.0056	1289	39	7.001	1.130	8.36E-06	Yes
Seal B	5.0989	0.0056	1398	47.5	6.480	0.917	1.16E-05	No

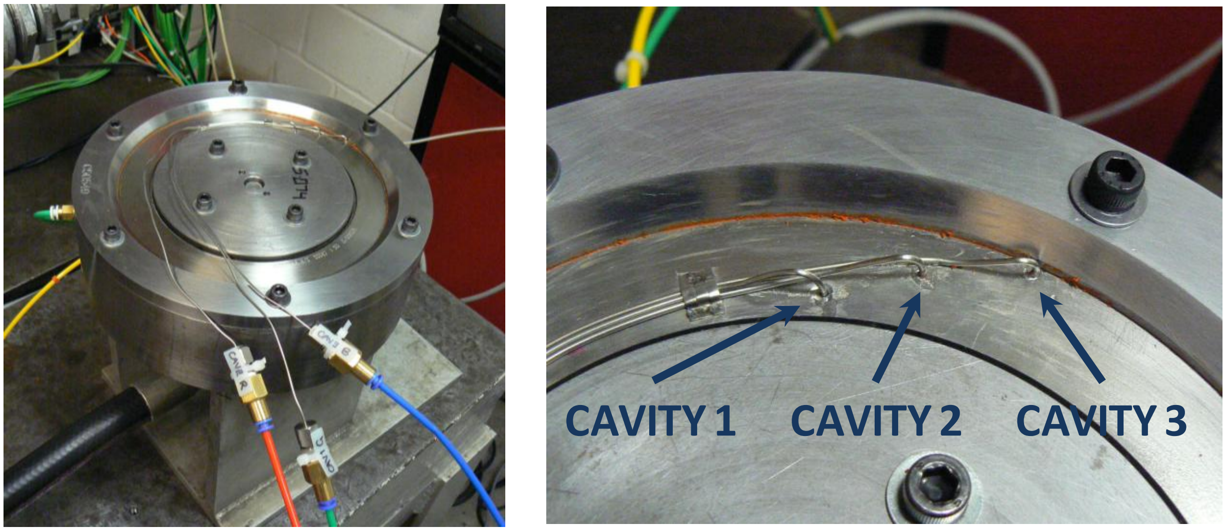

Figure 6 Static Brush Seal rig with Back Plate pressure taps

Tests were run with 5 different rotor sizes to evaluate the effects of clearance and interference on not only the back plate pressure distributions but also the leakage. The tests were run with 0.020” and 0.012” radial clearance, a line on line condition and with 0.010” and 0.020” radial interference. Results from these tests are shown in Figures 7 to 14.

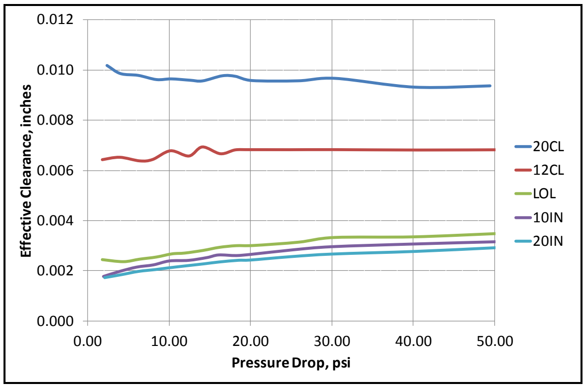

Figure 7 Seal A Sealing Performance

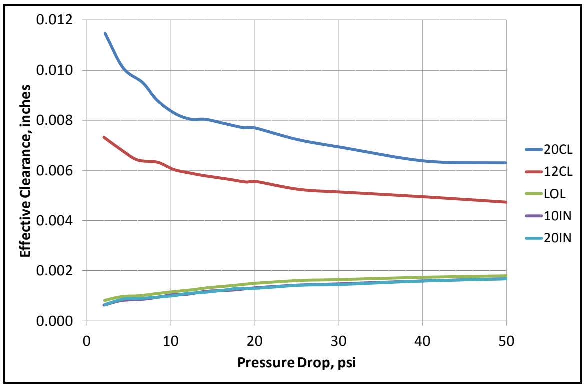

Figure 8 Seal B Sealing Performance

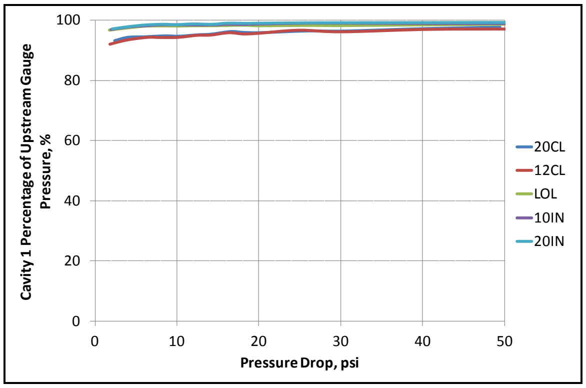

Figure 9 Seal A Cavity 1 Pressure

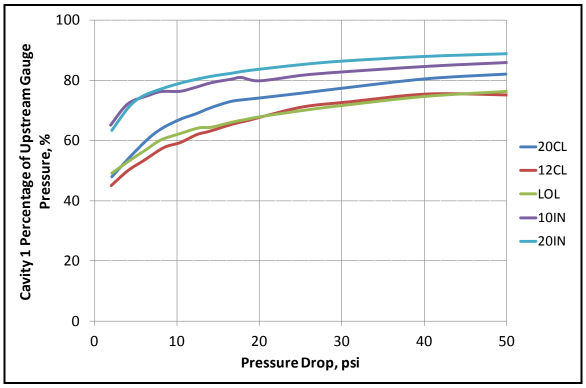

Figure 10 Seal B Cavity 1 Pressure

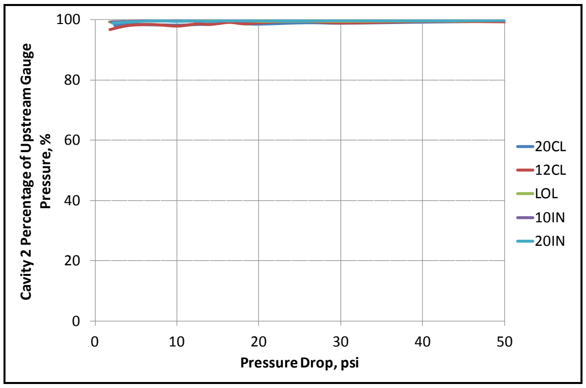

Figure 11 Seal A Cavity 2 Pressure

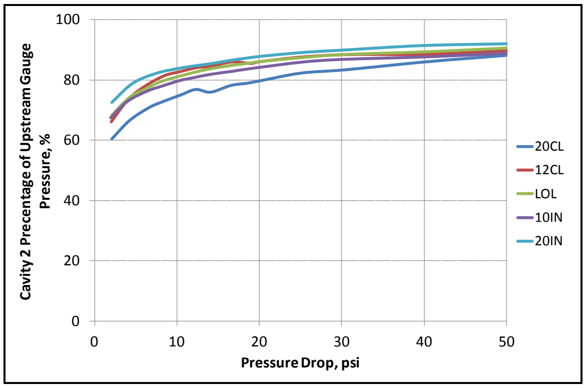

Figure 12 Seal B Cavity 2 Pressure

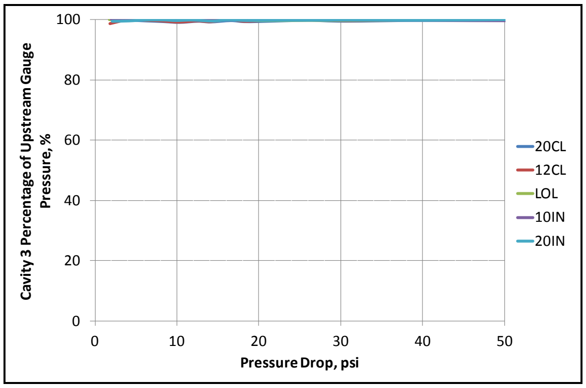

Figure 13 Seal A Cavity 3 Pressure

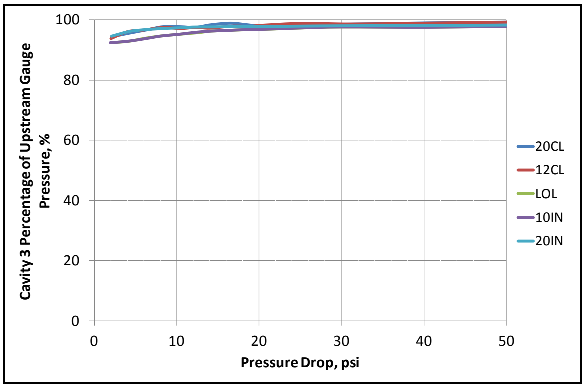

Figure 14 Seal B Cavity 3 Pressure

As expected the pressure balanced seal A has much higher back plate pressures, seal B however does have better blowdown(15) performance and lower baseline leakage.

Comparisons of the CFD and test data are shown in the graphs in Figures 15 to 17 for seal B only. It can clearly be seen that the analytical results match the test data very well.

The pressure distribution through the bristle pack is also needed for the FEA model, this data is extremely hard if not impossible to gather experimentally, Cross have in the past gathered this data at the bristle tip to rotor interface(5) but it is not straightforward to do as axial bristle deflections tend to complicate the understanding of the data. Cross have for many years used an in house 1D code to look at this distribution, so we decided that it would be good to compare the data from this code with the CFD data, this comparison is made in Figure 18.

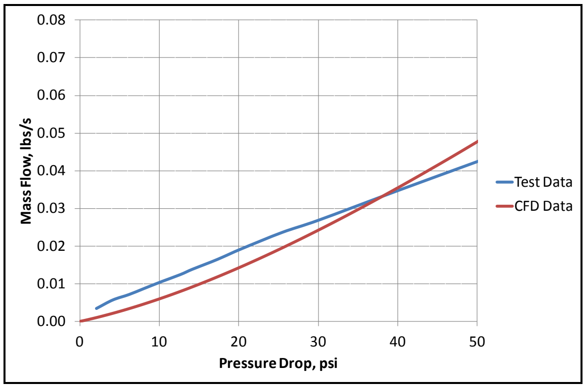

Figure 15 Seal B Mass Flow Comparison

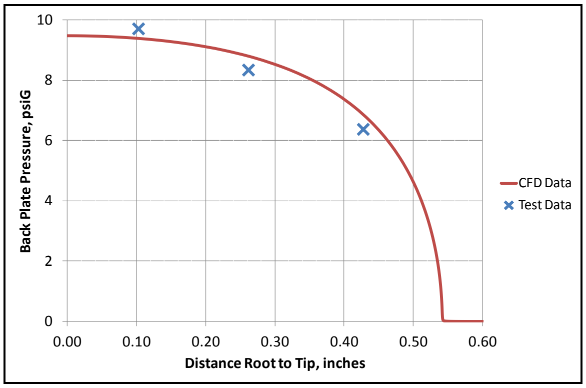

Figure 16 Seal B Back plate pressure at 10psi

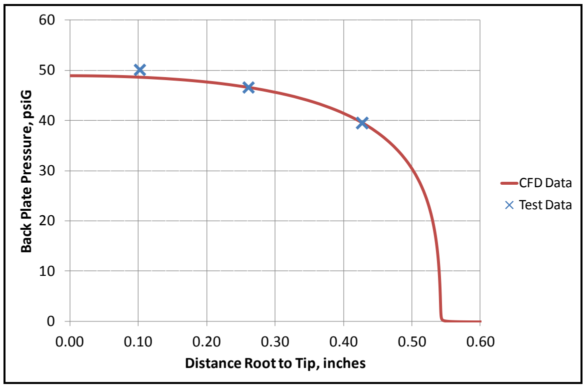

Figure 17 Seal B Back plate pressure at 50psi

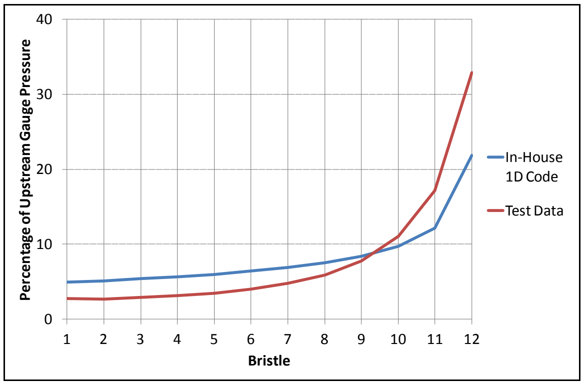

Figure 18 Seal B Tip pressures at 50psi

It can be seen that the CFD data shows all the same trends as the test data and 1D flow code data, the data match is not exact but we considered good enough to confirm that the CFD model data was acceptable to use as boundary conditions in the FEA model.

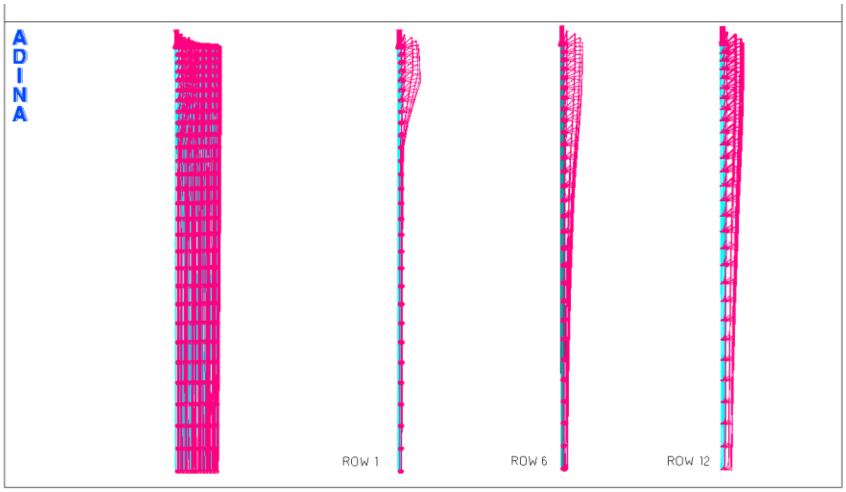

Figure 19 Pressures applied to bristles in the FEA Model

D. Implementation of CFD Boundary Conditions in FEA Model

Once confident that the CFD data was acceptable to use these boundary conditions were fed into the FEA model, Figure 19 shows that the pressures were applied to each leayer in the model. This is not yet an automated approach so it can take considerable time to assemble and todate we have only completed work for seal B

IV. Results from FEA Model

A. Stiffness Checking

The first runs of the model were made without the pressure loading, they were to simulate the stiffness checking, we have previously presented details of this experimental method(6). Photos of the test setup and deflected bristle shape are shown in Figures 20 and 21 below.

Figure 20 Stiffness Checking Machine

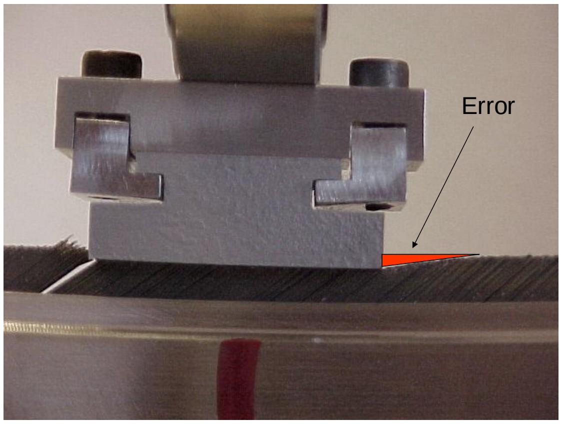

Figure 21 Deflected Bristle Shape

To compensate for the effort, shown by the red triangle, Cross performs the test twice, we use a 0.5” and 1.0” long shoe and subtract the 0.5” data from the 1.0” data. We then reduce the data to load per single bristle based on the number of bristles incontact with the 0.5” long arc. Data comparing the FEA results to the test data are shown below in Figures 22 and 23.

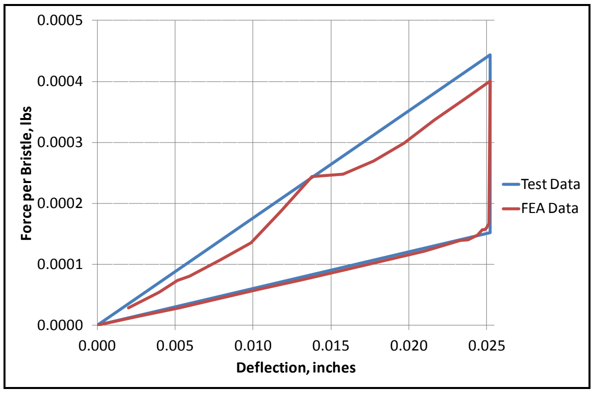

Figure 22 Seal A Stiffness Check

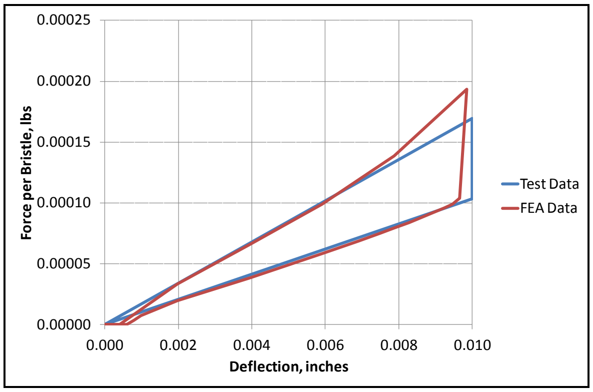

Figure 23 Seal B Stiffness Check

From the comparison data of the FEA and the test data it is clear we have a very good match. The coefficients of friction used in the models were 0.2 for bristle to bristle contact and 0.28 for all other contact. The magnitude of the forces is very similar in both cases as is the magnitude of the hysteresis loop. Seal A is a very soft seal with a very long free bristle length, this has given increased hysteresis.

The comparison of the test data with the FEA data confirmed that the model was a pretty good match to test data, this confirms that the cyclic boundary conditions in the model work well and that the model represents the physical attributes of the seals closely. The confidence gained in the model from the stiffness test comparison allowed us to continue and add the pressure distributions, from the CFD work, into the model

B. Radial Offset Recovery

Once the pressure distributions from the CFD were fed into the model it allowed us to look at the hysteresis of the seals during transient radial closure events like those illustrated in Figure 2. The model was run by firstly applying the pressure drop and then applying a radial movement of 0.010” on the simulated rotor into the bristle pack and then removing it.

The hysteresis loop obtained is shown in Figure 24.

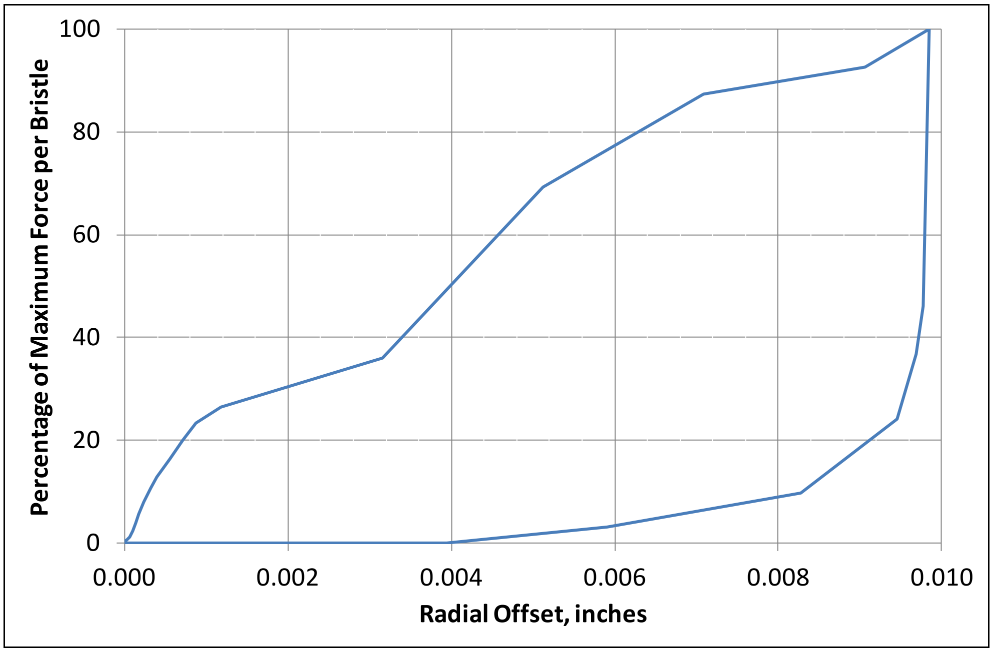

Figure 24 Hysteresis loop obtained from Radial Offset Test at 10psi, Seal B

The hysteresis loop obtained is interesting in the fact that as the rotor retracts from the bristle pack the bristles stop recovering with an interference of 0.004”. This is very typical of a brush seal at pressure drops greater than 3 or 4 psi, once the pressure is totally removed the bristles recover fully. Figures 25 and 26 show the fully deftected bristle pack model and the model when the offset has been fully removed.

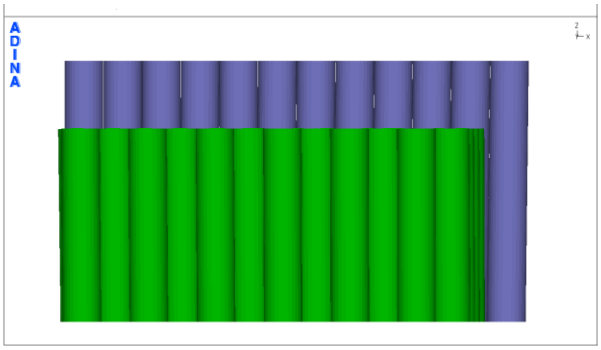

Figure 25 Deflected Bristle Pack

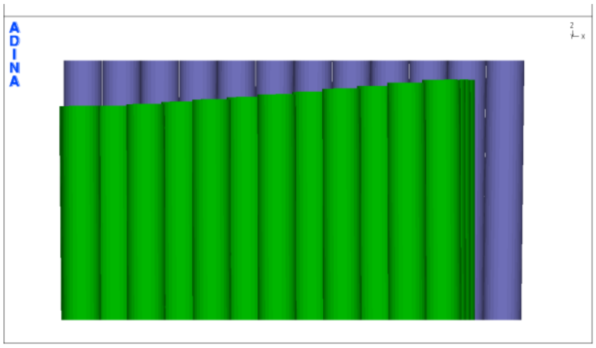

Figure 26 Offset Fully Removed

Figure 26 very clearly shows that the bristles have not fully recovered back to their initial position, the upstream part of the pack has recovered better than the ones up against the back plate. The front layers are always considered to be more able to move freely and the pressure drop across them is typically lower, the model appears to have captured this very well. The magnitude of the recovery looks about correct with the front layer recovering 75% but the back layer only 35% of their way back to their initial positions.

V. Conclusion

An FEA model of a brush seal pack has been developed using the commercial code ADINA. The parametric model is flexible on its inputs and features full 3D contact, it can run with and without pressure loading and comparisons with test data is encouraging.

The model appears to capture well the hysteresis loop obtained during stiffness checking, with results of a very similar magnitude to those obtained experimentally.

The model was also run with pressure loadings obtained from a porous flow CDF model, the preliminary results obtained indicate that the hysteresis obtained is similar in magnitude to that expected during offset recovery tests.

Acknowledgments

Cross Manufacturing has funded all work described in this paper and we would like to thank the Directors for allowing us to publish this data. Thanks also go to the dedicated team of engineers and manufacturing staff at Cross who work together to produce products of outstanding quality.

References

1. Flower, R. “*Brush Seal Development System”.* Orlando : AIAA/SAE/ASME/ASEE Joint Propulsion Conference, 1990. AIAA-90-2143.
2. Crudgington, P and Bowsher, A. “*Brush Seal Pack Hysteresis”.* Indianapolis : AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2002. AIAA-2002-3794.
3. Prithwish, B and Pawtucket, R I. “*Brush Seal Device Having A Recessed Back Plate”.* United States, 1995. PN:5,401,036, Mar. 28. 1995.
4. Morrison, M K, Withers, P A, Jones, T V, Wood, P E. “*Brush Seal”.* United States, 1998. PN:5,799,952, Sept. 1. 1998.
5. Crudgington, P. “*Recent Brush Seal and Testing Development at Cross”.* Salt Lake City : AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2001. AIAA-2001-3480.
6. Crudgington, P, Bowsher, A, Lloyd, D. “*Bristle Angle Effects on Brush Seal Contact Pressure”.* Denver : AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2009. AIAA-2009-5168.
7. Bayley, F J and Long, C A. “*A Combined Experimental and Theoretical Study of Flow and Pressure Distributions in a Brush Seal”.* Cologne : ASME Journal of Engineering for Gas Turbines and Power, 1992. 92-GT-355.
8. Hendricks, R C, Wilson, J, Wu, T Y, Flower, R, Mullen, R L. “*Bidirectional Brush Seals - Post-Test Analysis”.* OPA N.V, 1999. International Journal of Rotary Machinery Vol.5 No. 3 pp.167-180.
9. Willinger, R. “*Computation of the Flow in Turbomachinery Brush Seals Using Porous Medium Approach”.* Vienna : Instiute for Thermodynamics and Energy Conversion.
10. Dogu, Y. “*Investigation of Brush Seal Flow Characteristic Using Bulk Porus Medium Approach”.* Atlata : ASME Turbo Expo, 2003. GT2003-38970.
11. Pugachev, A O and Helm, P. “*Calibration of Porus Medium Models for Brush Seals”.* IMechE, 2009. Vol.223 Part A:J.Power and Energy.
12. Pugachev, A O and Deckner, M. “*CFD Prediction and Test Results of Stiffness and Damping Coefficients for Brush-Labyrinth Gas Seals”.* Glasgow : ASME Turbo Expo, 2010. GT2010-22667.
13. Cieslewicz, S M, Jozwik, k and Willinger, R. “*CFD-Simulation for Advanced Turbomachinery Sealing Technologies: Brush Seals”.* Vienna : Vienna University of Technology, 2004.
14. ADINA CFD Theory & Modelling Guide June 2010, ADINA R & D, Inc. 2010-2011
15. Crudgington, P and Bowsher, A. “*Brush Seal Blow Down”.* Huntsville : AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 2003. AIAA-2003-4697.