NUMERICAL SIMULATIONS AND AN EXPERIMENTAL INVESTIGATION OF A FINGER SEAL

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CONCEPT AND COMPONENTS

General Configuration

Full Wafer of Padded Fingers (8.5” ID, 9.666” OD, 81 Fingers) and details (b, c) of the Arrangement of the High and Low Pressure Fingers
DESIGN PARAMETERS
(Variations in the Design of the Finger Stick and Foot)

Besides sealing, the other main goal of a successful finger seal design is to exhibit appropriate compliance to outside forces. The ability of the seal to ride or float along the rotor without rubbing or excessive heating is essential to the successful operation of the seal.

The compliance of the finger must only occur in the radial plane;

The seal needs to be as sturdy as possible in the axial direction.

The compliant finger that moves radially outward with rotor growth and motion has to be able to ride the rotor back down as the rotor diameter recovers or the rotor moves “away”.

Thus there is an optimum stiffness for the finger;
DESIGN PARAMETERS (cont’d)
(Variations in the Design of the Finger Stick and Foot)

(1) $D_{cc}$ Stick Arcs Circle of Centers.
(2) $R_s$ Stick Arc Radius.
(3) $D_b$ Finger Base Diameter.
(4) $D_f$ Foot Upper Diameter.
(5) ‘a’ Finger Repeat Angle.
(6) $L_s$ Finger Interstice Width.
(7) $L_c$ Circumferential Foot Length.
(8) ‘b’-Laminate thickness.

View of Finger Stick Cross-Section

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1) $D_{cc}$ Stick Arcs Circle of Centers

When the diameter of the circle of centers ($D_{cc}$) of the finger stick arcs was increased, while all other dimensions remained the same, the sticks became thicker and pointed more directly toward the center of the seal.

The two figures show the change in the shape of the finger stick when the circle of centers was increased to the diameter of (a) $D_{cc} = 4.000$-in from (b) $D_{cc} = 1.575$-in.
(2) $R_s$ Stick Arc Radius.
The two figures (a) and (b) show the change in the shape of the finger stick when the arc radius was increased to $R_s = 5.000$-in from $R_s = 4.511$-in.

NOTE:
The increase in $R_s$, while keeping $D_{cc}$ constant, caused the sticks to curve more concentric with the inside diameter of the seal, and consequently make the stick length much longer.
(3) \(D_b\) Finger Base Diameter. 

Figures (a) and (b) shows the seal in which the finger base diameter had been changed to (a) \(D_b = 8.900\)-in. from (b) \(D_b = 9.169\)-in.

**NOTE:**

When the finger base diameter, \(D_b\), was changed, the stick length, \(L_{st}\), changes. With all other dimensions kept constant, this variation *only* altered the length of the stick; the cross-sectional height, \(h\), and the angle at which it attaches to the pad (foot) remained the same.
**4) D_f, Foot Upper Diameter.**

Figures (a) and (b) shows the altered foot geometry as the upper foot diameter was changed to (a) D_f = 8.800-in from (b) D_f = 8.600-in. The mass of the foot can be altered by changing the upper foot diameter, D_f.

**NOTE #1:**

Altering the mass does not affect the equivalent stiffness of the finger, but it does have an impact on the finger dynamics.

Increasing D_f also shortened the effective stick length, L_{st}, which significantly affects the finger stiffness.

**NOTE #2:**

D_b also affects the finger stiffness length L_{st} (see previous slide)
(5) ‘a’ Finger Repeat Angle.

Figures (a) and (b) shows the change to a 40 finger seal, (a) \( a = 9.000° \) repeat angle, from an 81 finger seal, (b) \( a = 4.444° \) repeat angle. It is the repeat angle, \( a \), of the finger stick arcs that determines how many individual fingers will be in the total seal.

From the standpoint of the stick stiffness, the change in ‘a’ will cause a significant change in \( h \); doubling the height increased the area moment of inertia, and consequently the stiffness by eight fold, as summarized in the following Table for an increase in \( a \) to 9.000°.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Original Value</th>
<th>Value change with the Increase of ‘h’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Stick Length</td>
<td>( L_{st} )</td>
<td>1.6108-in SAME</td>
</tr>
<tr>
<td>Cross-section Base</td>
<td>( b )</td>
<td>0.030-in SAME</td>
</tr>
<tr>
<td>Cross-section Height</td>
<td>( h )</td>
<td>0.045-in 0.090-in</td>
</tr>
<tr>
<td>Area Moment of Inertia</td>
<td>( l_{xx} )</td>
<td>2.28x10^{-7} in^4 1.822x10^{-6} in^4</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>( E )</td>
<td>31x10^6-psi SAME</td>
</tr>
<tr>
<td>Stick Stiffness</td>
<td>( k_{stick} )</td>
<td>5.07-lbf/in 40.55 - lbf/in</td>
</tr>
</tbody>
</table>
Design Parameters (cont’d)
(Variations in the Design of the Finger Stick and Foot)

(6) Is Finger Interstice Width

Figures (a) and (b) shows a finger seal with a change to an (a) Is = 0.025-in interstice from an (b) Is = 0.015-in interstice between fingers. The interstices, I_s, (cutouts) between the individual fingers are what give the fingers the ability to move independently of each other.

NOTE:
The added space between the fingers allows the seal to open to a greater maximum diameter, but it also allows greater potential leakage. Thus one has to optimize between freedom of movement and minimum leakage.
(7) \( L_c \) Circumferential Foot Length.

Figures (a) and (b) show a foot whose toe and heel were removed such that the arc length is reduced to (a) \( L_c = 0.115 \) in from (b) \( L_c = 0.315 \) in. Keeping all other parameters constant, the circumferential arc length, \( L_c \), of the foot itself was considered for optimization.

Resultant Contours Comparisons for a Change in \( L_c \) to 0.115-in from 0.315-in: (a) Deflection Dither, (b) Stress Dither.
(8) **Laminate thickness.**

The final geometric variation of the finger portion that was evaluated was the cross-sectional thickness, \( b \), of the individual finger laminates. Stiffness values, \( k_{\text{stick}} \), were determined for a cross-sectional thickness ranges from \( b = 0.010'' \) to \( b = 0.045'' \).

**FEM Loading and Boundary Conditions for Investigation of Finger Out-of-Plane Twisting as a function of Finger Thickness, \( b \).**
The finger seal obtains its hydrodynamic lifting capabilities from the pattern of the padded fingers underside, which “rides” the surface of the shaft. The objective in the design of the pad was to determine an optimal configuration that would enable the pad portion to lift from the rotating rotor and to run on a thin film of air during operation while minimizing the leakage rate.

The desirable motion of the pad is one that is in sync with the motion of the stick while minimizing its rotation out-of-plane with respect to the stick. If the pad rotated around its heel, it could potentially both open the clearance for leakage and “dig” into the shaft at the origin of the pad rotation. Therefore the design of the pad had to minimize this situation.

Radial Out-of-Plane Twisting as Viewed from Underneath the Pad and from the Low-Pressure Side: (a) Stick Thickness of b=0.015-in, (b) Stick Thickness of b=0.030-in

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Variations in Finger Pad Design

Shape of the underpad surface Axial Out-of-Plane Twisting for Stick Thickness of b=0.015-in and b=0.030-in

Another view of pad and stick deformation

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FINGER BEHAVIOR WITH ROTATING SHAFT AND AXIAL PRESSURE DIFFERENTIAL Δp=5 PSI

x-, y- and z- Displacements

Experimental Conditions:
Rotation: 7000 RPM
Axial pressure: 0 to 5 PSI

Photos of the fingers (the region shown in the above pictures) are taken by two cameras from different angles at the same time. The x (circumferential), y (radial), and z (axial) displacements are obtained by analyzing the pairs of the images.
Fingers Motion and Deformation Animation

10,000 RPM

10kRPM, 5 psi
FINGER BEHAVIOR WITH ROTATING SHAFT AND AXIAL PRESSURE DIFFERENTIAL Δp=5 PSI

Time History Displacement of The Stage Points

- Circumferential
- Radial
- Axial

Stage points: #1, #2, #3, #4, #5

The color of the stage points # corresponds to the color of the curves above.

Positive: out of the plane
Negative: into the plane

Time (sec)
CONCLUDING REMARKS (1)

Finger Behavior with Rotating Shaft and Axial Pressure Differential

- All the fingers vibrate because of the rotation of the shaft. Lifting force on the pad is very sensitive to the clearance between the pad and the shaft surface.
- In one coordinate direction, all the fingers move in the same manner.
- At different radial locations, the x-displacement varies in the same manner.
- The y- and z-displacements are different at different radial locations.
- The z-displacement is smallest at the root of the fingers and at the back plate supporting point.
FINGER BEHAVIOR WITH ROTATING SHAFT
No Axial Pressure Differential

Stage Point #5 Close to the finger root
Stage Point #1 Close to the finger tip

Displacement X (in)
Displacement Y (in)
Displacement Z (in)
CONCLUDING REMARKS (2)

Finger Behavior with Rotating Shaft and No Axial Pressure Differential

- With the shaft rotating while no axial pressure drop, all the fingers move/vibrate independently. There is no phase correlation observed between the vibrations of the fingers.
- The displacement decreases from the finger tips to the finger roots.
- At one location, the displacement magnitude of the vibration in three (x-, y-, z-) directions are roughly the same.
- The movements of the fingers proved that all the fingers are lifted by the pressure build up under the bad due to the rotation of the shaft.
FINGER BEHAVIOR WITH AXIAL PRESSURE DIFFERENTIAL

Axial Pressure Shock: 0-20-0 PSI, No Shaft Rotation,

From initial state, pressure was increased from 0 to 20 psi and then decreased to 0 psi. The test was to investigate the finger behaviors under such a pressure shock.

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CONCLUDING REMARKS (3)

Finger Behavior with Axial Pressure Differential, No Shaft Rotation.

- With axial pressure drop only, all the fingers move in the same manner since all the fingers subject to roughly the same axial flow and axial pressure drop.
- The deformation/bending of the fingers are three-dimensional.
- Displacement distributions show sharp jumps between the fingers, which indicates that they can move independently.
Grid Details for the Pressure, Flow and Temperature Calculations.

a) Solid representation of the two rows of fingers viewed from below
b) Corresponding representation of the fluid film contained between the rotor and the assembly of fingers.
c) Detail of the cell structure in the fluid film below and in-between HP and LP pads.
d) Fluid film grid structure under the HP finger
e) Fluid film grid structure under the LP finger
Flow trajectories visualized with individual 4-finger cell showing circumferential flow. a) tracers showing circumferential flow; b) 3-D flow between low pressure fingers, c) frontal view of flow in b)
Boundary conditions for the Finger Seal. Schematic Cross Section with Two Rows of Padded Low- and Pad-less High Pressure Fingers
Comparison between pressure magnitude development under the fingers when incompressible ($\rho, \mu = \text{const}$) and perfect gas laws are used.
Comparative temperature map for the incompressible and perfect gas law cases. The adiabatic case.
Comparison between pressure profiles when the linear velocity of the rotor is increased from 216 m/s to 432 m/s. The isothermal case.
TEMPERATURES: ALMOST ISOTHERMAL (1000 W/m²K)
216 m/s and 432 m/s

Temperature development when the angular velocity is varied from 216 m/s linear, to 432. The almost isothermal case.
Single Finger Geometry (Solid-Fluid Interaction)
Moving Finger

Temperature (a) and strain (b) in the finger pad and leg. Adiabatic conditions on finger and rotor surfaces.

Rotor rotates at 30000 rpm

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Lift of the pad central section with angular velocity

 Shaft speed (x10³ rpm)

 y-displacement (µm)

- Rotor surface: adiabatic
- Finger surface: adiabatic
- Finger pad bottom: interface
- Initial down-stream clearance: 6.35 µm
- Initial up-stream clearance: 19.05 mm

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a) Pure Hydrodynamic Pressure build up under the lifting finger

b) Pure Hydrodynamic Pressure build up under the rigid finger

c) Pure Hydrodynamic Pressure build up under the lifting finger

20,000 rpm

30,000 rpm

40,000 rpm

Pressure
\( \frac{N}{m^2} \)

0
800
1600
4.2E5
2.1E5
10E5
0
Pure Hydrodynamic Temperature build up under the lifting finger

Rotor and pad upper surface are adiabatic. The pad itself allows 3-D energy transfer

Pure Hydrodynamic Temperature build up under the rigid finger
Comparison between adiabatic and thermal conditions

(a, b) Adiabatic rotor and finger surfaces.

(a', b') Isothermal rotor and finger surfaces at $T_0$.

The pressure and temperature in the center of the air film for two thermal boundary conditions with rotor rotating at 30000 rpm.
EQUIVALENT DYNAMIC MODEL

Fixed positions due to anchoring to the torroidal root

Moving Boundary

Fluid layer equivalent Spring-Damper

a) b) c)

Solid model and Equivalent Spring-Mass-Spring/Damper representation for use in the equation of motion simulation

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Finger assembly free vibration when $k_{SF_{eq}}$ is varied:

a) $\Delta p_c = 6.9$ kPa (1psi); b) $\Delta p_c = 34.5$ kPa (5psi); c) $\Delta p_c = 69$ kPa (10psi);
Finger following the rotor when Coulomb damping force and rotor angular velocity is varied. Finger stiffness is

\[ k_{SE}\text{psi} = 3.58 \frac{N}{m} \times (20.44 \frac{lbf}{in}); \]

a) 10,000 rpm (108 m/s); b) 20,000 rpm (216 m/s); c) 30,000 rpm (324 m/s); d) 40,000 rpm (432 m/s)

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DIARGAMS OF THE TEST SECTION
Overall installation
Electric, Oil and Air Circuits

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Frontal view of the rotor.
Track left on the rotor by the seal. Three was no contact between the seal and rotor during the run. Contact at start-up, liftoff-no contact, contact again at coast-down.
View of a sector of both HP and LP seals after running approx. 10 min at 9,950 rpm with no pressure differential across the seal.
FINGERS’ PAD UNDERSURFACE DETAILS

Enlarged view of two pads after the 10 min. run

Slight traces of wear

HP side
Direction of Rotor Rotation with respect to Finger Pads

LP Finger Underside Pads Surface Showing Ink Wear Marks after a Total Run Time of 97 min at a nominal speed of 9,950 rpm; This included 4 start-ups and 4 coast-downs. Seal Quadrants Positioned as Viewed from the Low-Pressure Side

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LEAKAGE FLOW PERFORMANCE SUPERIMPOSED ON ROTATION, TEMPERATURE AND PRESSURE DIFFERENTIAL

![Graph showing leakage flow performance superimposed on rotation, temperature, and pressure differential.](image)

- **Leakage (SLPM)**
- **Rotation (rpm)**
- **Pressure (psi)**
- **Temperature (°F)**

**Legend:**
- HP Zones Pressures
- LP Zones Pressures
- LP Pads Temps
- TC 1
- TC 2
- TC 3
- TC 4
- TC 7
- Leaka
- g e
- Rotation

**Axes:**
- **Y-axis (vertical):** Pressure (psi), Temperature (°F), Leakage (SLPM)
- **X-axis (horizontal):** Time (min)

**Units:**
- **Pressure:** psi
- **Temperature:** °F
- **Leakage:** SLPM
- **Rotation:** rpm

**Data Points:**
- Pressure values: 0, 3, 6, 9, 12, 15, 18, 21 psi
- Temperature values: 0, 30, 60, 90, 120, 150, 180, 210 °F
- Leakage (SLPM) values: 0, 3000, 6000, 9000, 12000, 15000, 18000, 21000 psi

**Time:**
- 0 to 45 minutes

**Additional Information:**
- November 8, 2005
- NASA/CP—2006-214383/VOL1

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FLOW FACTOR VS. PRESSURE DIFFERENTIAL

\[ \Phi = \frac{m \sqrt{T_{avg} + 459.60}}{P_u D_{seal}} \]

- Rotation Run 1
- Rotation Run 2
- Rotation Run 3
- Rotation Run 4

Chamber High Pressure (psi)