NUMERICAL SIMULATIONS AND AN EXPERIMENTAL INVESTIGATION OF A FINGER SEAL

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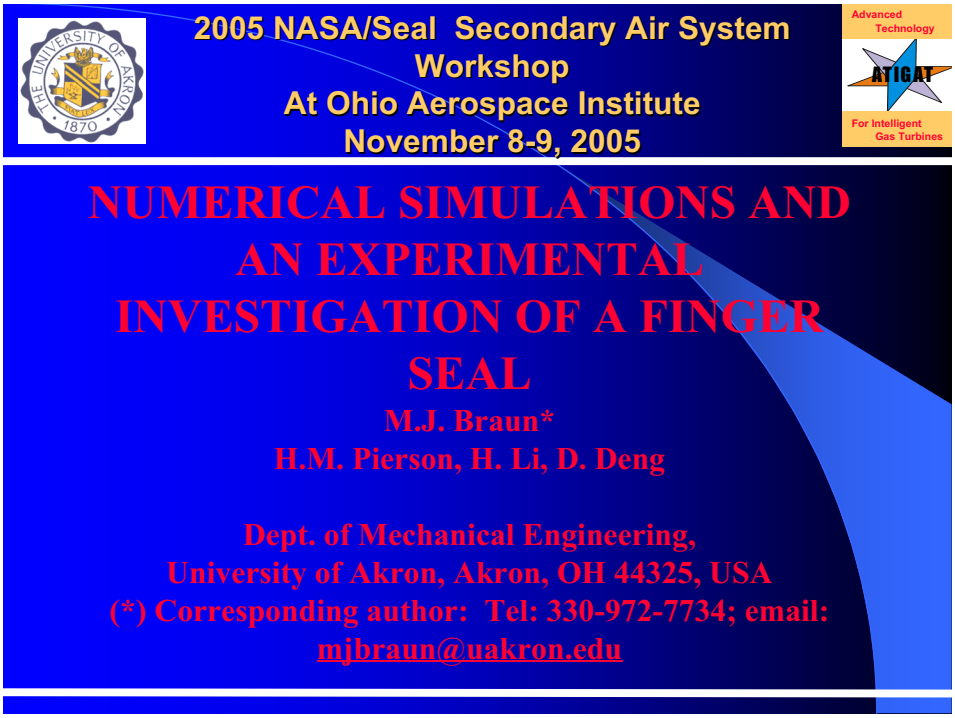
University of Akron
Akron, Ohio



ACKNOWLEDGEMENT

The authors want to express their gratitude to M. Proctor and B. Steinetz of NASA Glenn Research Center, Cleveland, Ohio for the financial support and technical consultations.

CONCEPT AND COMPONENTS

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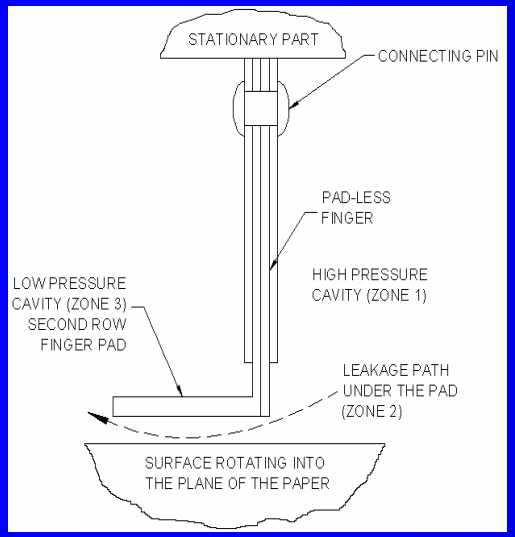
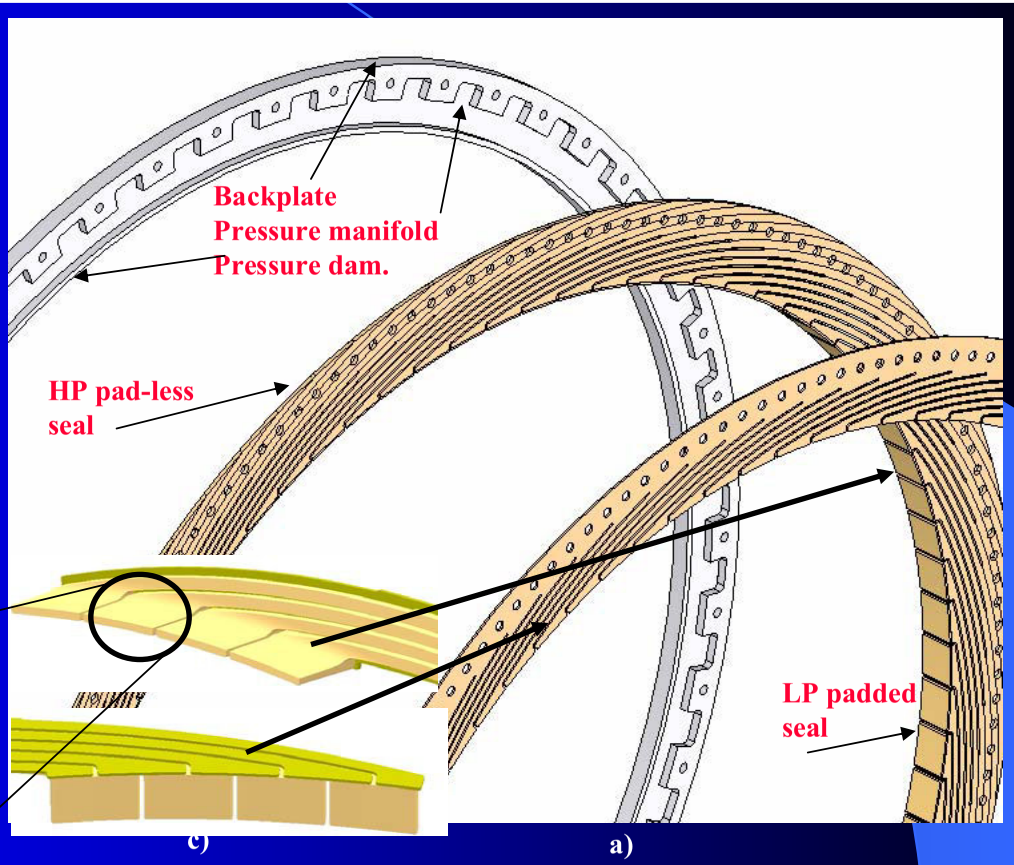
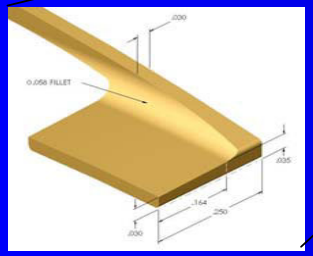


General Configuration





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

ACTUAL HARDWARE

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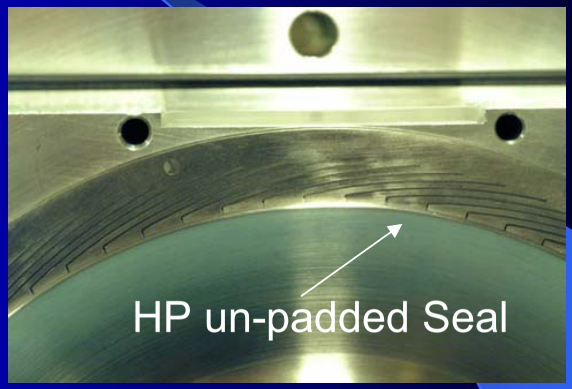

Manufactured by:
RF Cook
Stow, OH 44224

Padded and Unpadded Sections of HP- and LP-seals

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DESIGN PARAMETERS

(Variations in the Design of the Finger Stick and Foot)

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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)

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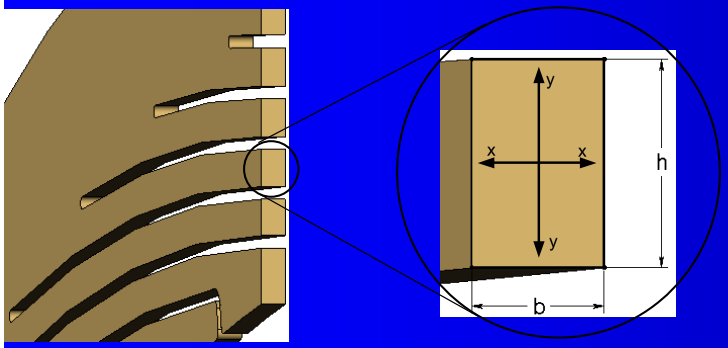
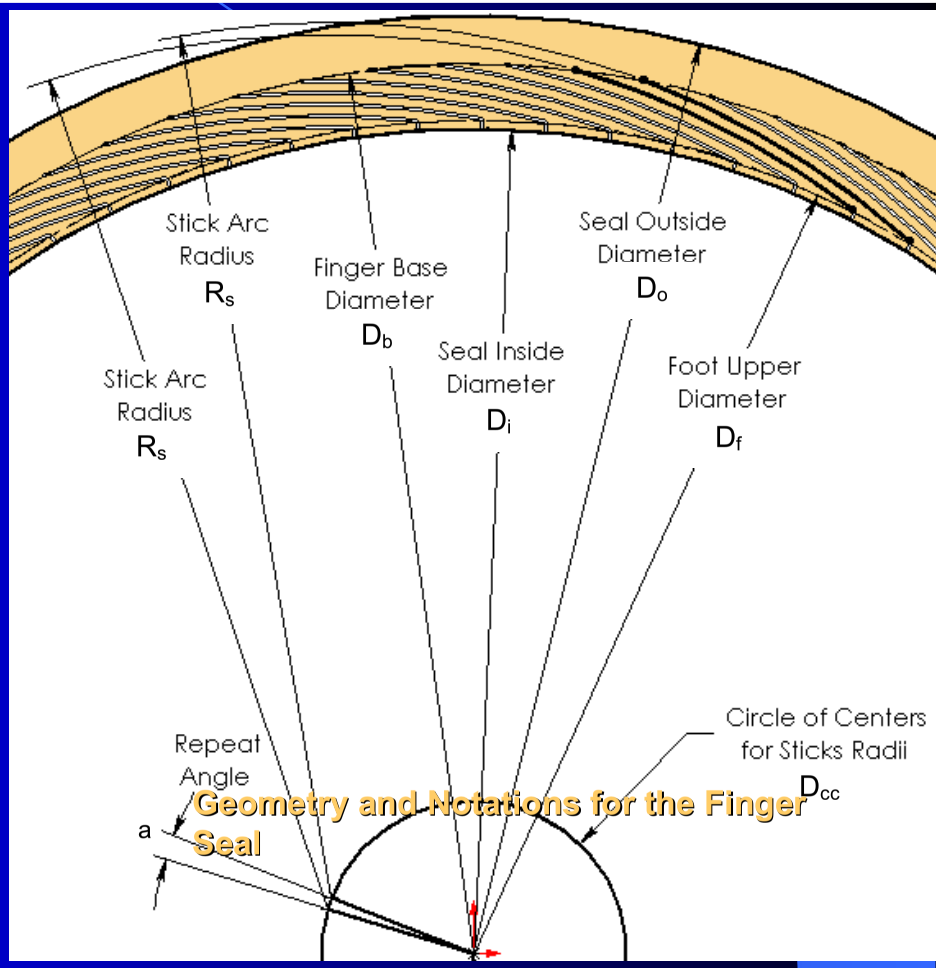
(1) D_{cc} Stick Arcs Circle of Centers.
(2) R_s Stick Arc Radius.
(3) D_b Finger Base Diameter.
(4) D_f Foot Upper Diameter.
(5) 'a' Finger Repeat Angle.
(6) l_s Finger Interstice Width.
(7) L_c Circumferential Foot Length.
(8) 'b'-Laminate thickness.



View of Finger Stick Cross-Section



Geometry and Notations for the Finger Seal

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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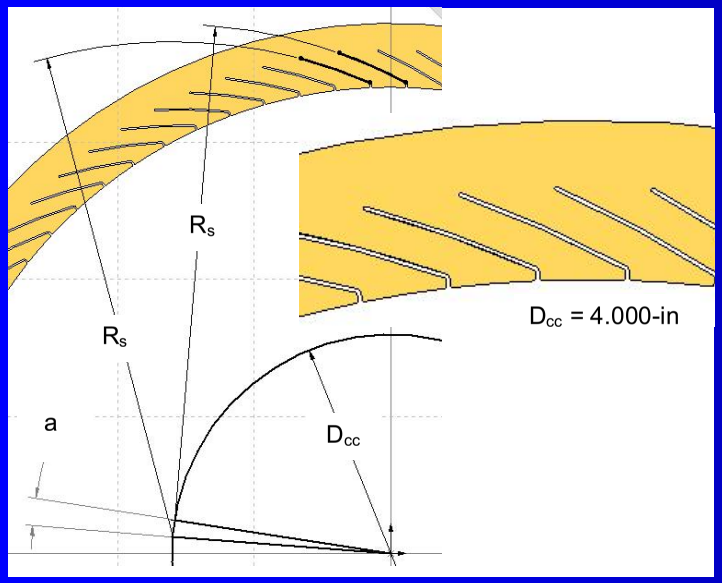
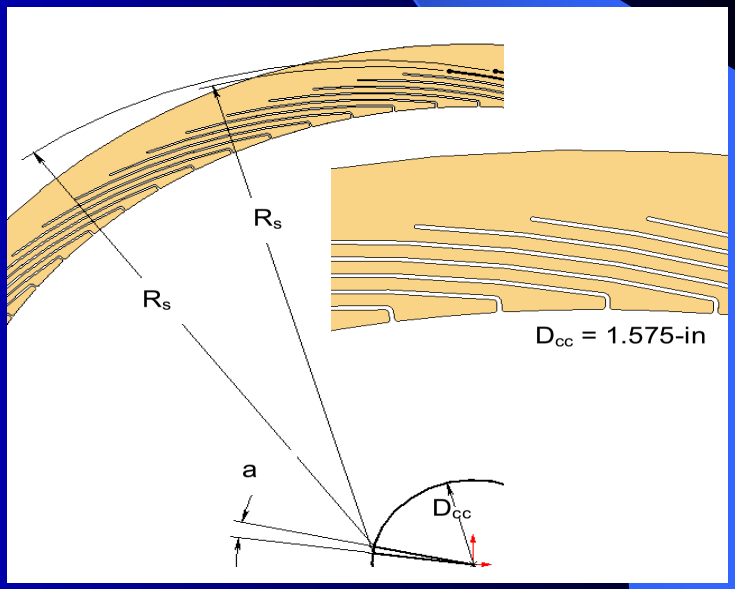
1)D_{cc} Stick Arcs Circle of Centers

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





DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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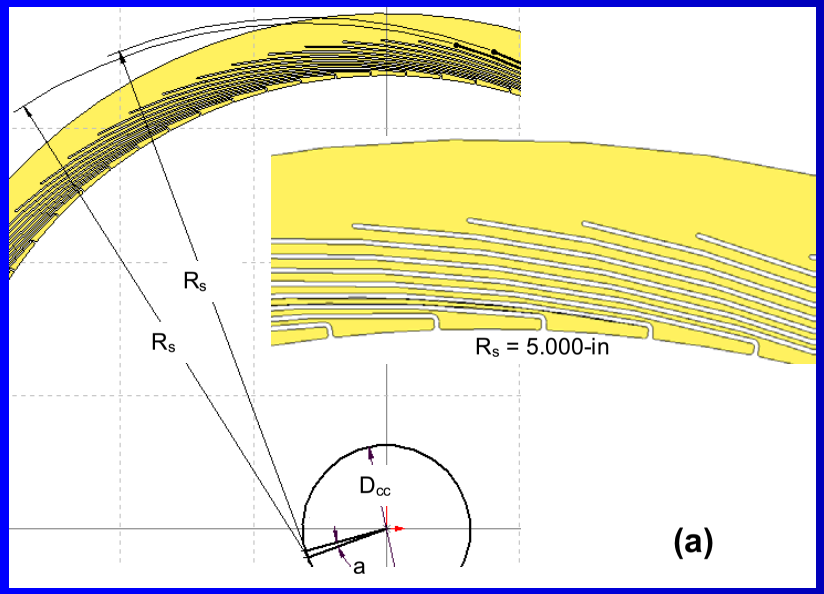
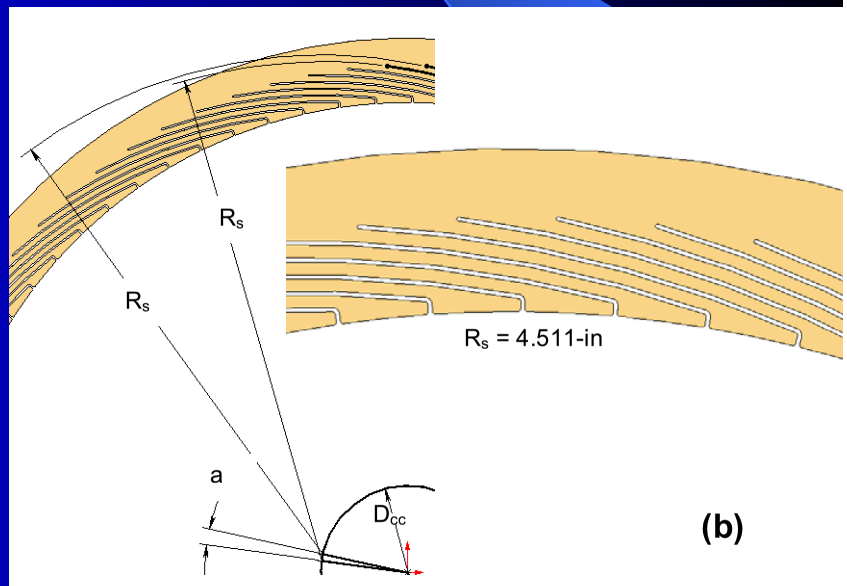
(2) R_s Stick Arc Radius.

The two figures (a) and (b) show the change in the shape of the finger stick when the arc radius was increased to Rs = 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.





DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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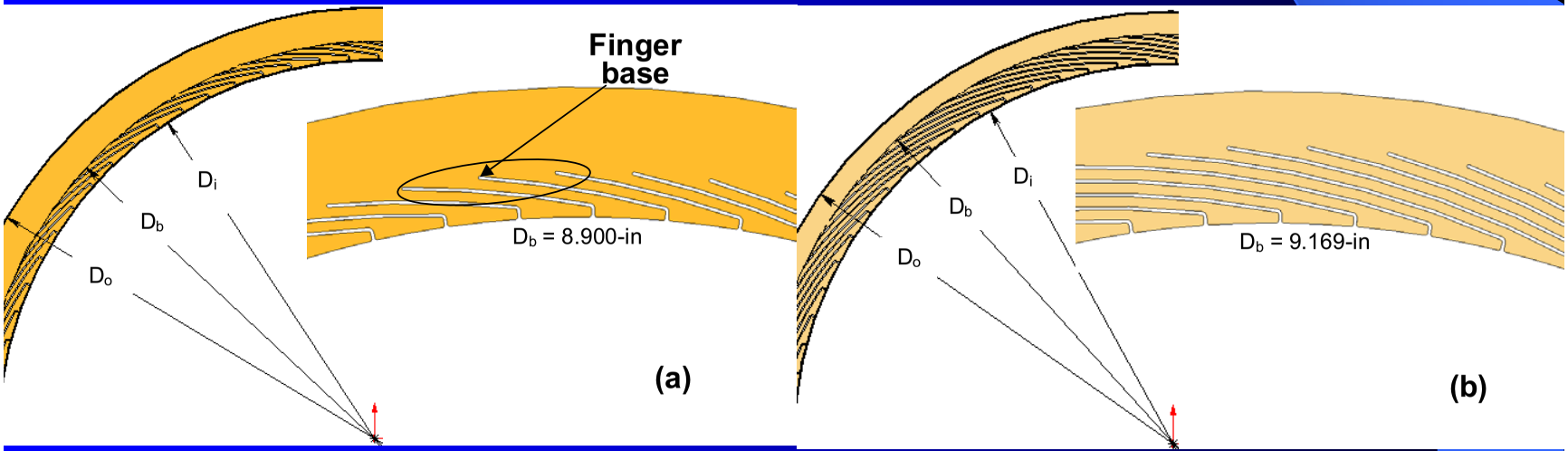
(3) D_b Finger Base Diameter.

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



DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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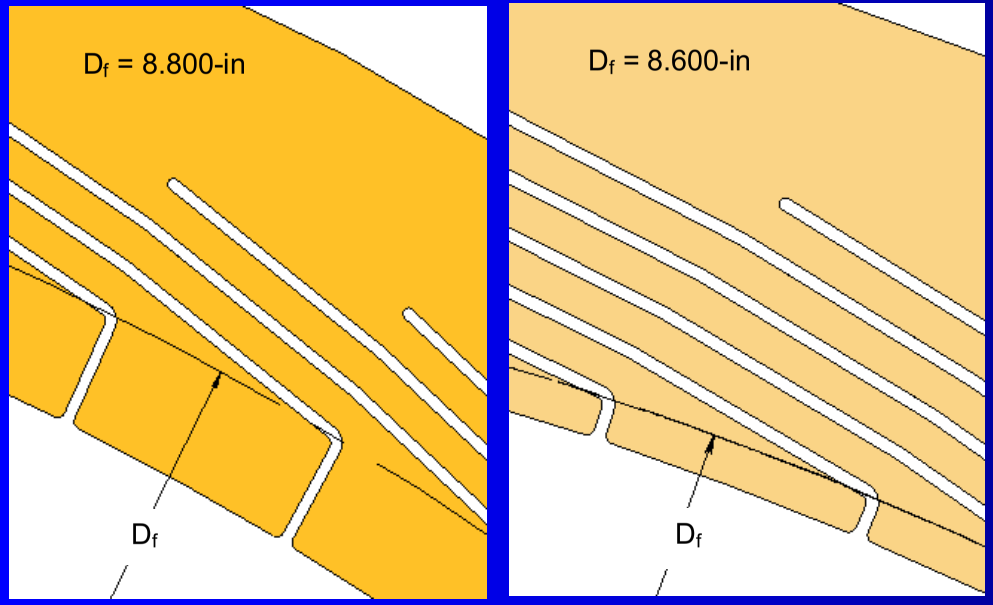
4) D_f Foot Upper Diameter.

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



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)

November 8, 2005

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

Advanced Technology

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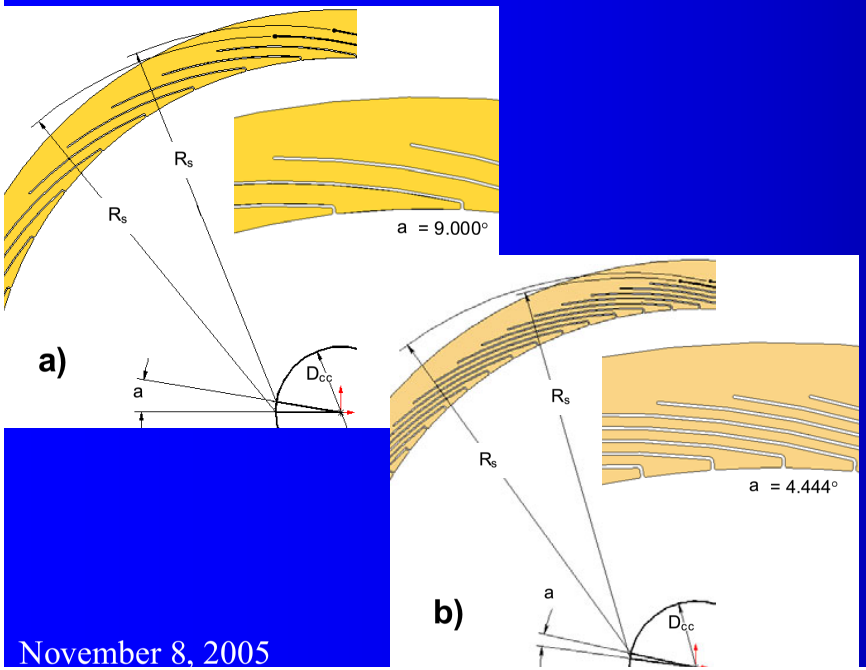
For Intelligent Gas Turbines

(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 9.000º.



	Symbol	Original Value	Value change with the Increase of 'h'
Effective Stick Length	L_{st}	1.6108-in	SAME
Cross-section Base	b	0.030-in	SAME
Cross-section Height	h	0.045-in	0.090-in
Area Moment of Inertia	I_{xx}	2.28×10^{-7}-in^4	1.822×10^{-6}-in^4
Modulus of Elasticity	E	31×10^6-psi	SAME
Stick Stiffness	k_{stick}	5.07- lbf/in	40.55 - lbf/in

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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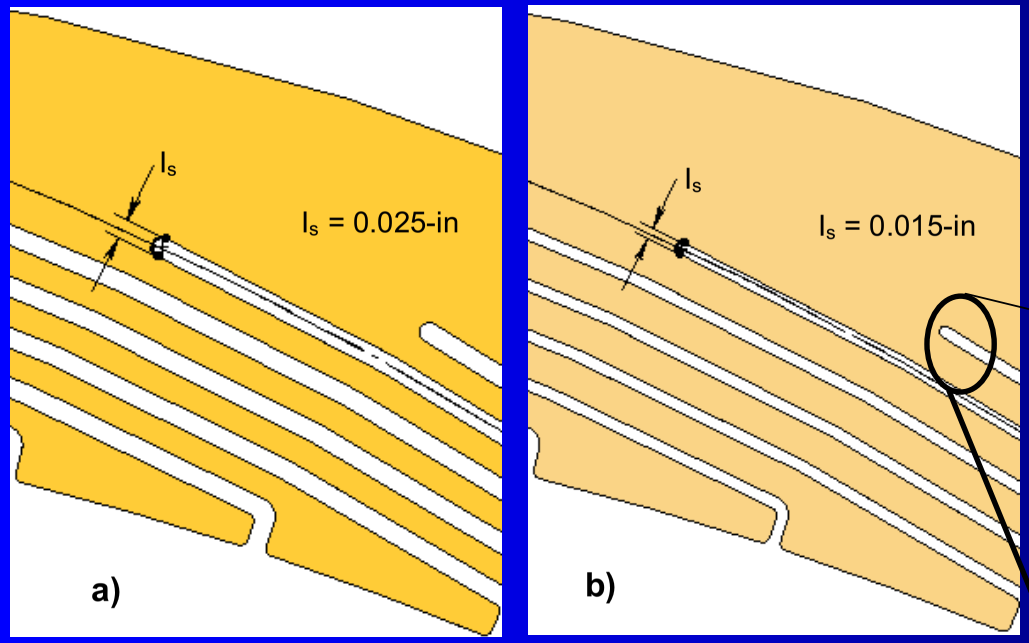
(6) Is Finger Interstice Width

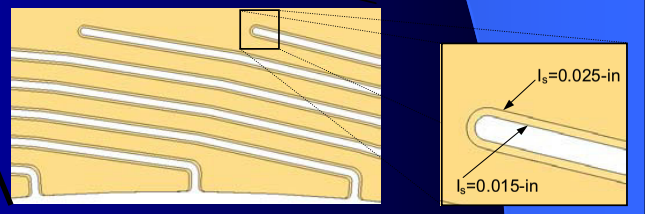
Figures (a) and (b) shows a finger seal with a change to an (a) Is = 0.025-in interstice from an (b) Is = 0.015-in interstice between fingers The interstices, I_s, (cutouts) between the individual fingers are what give the fingers the ability to move independently of each other.



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.



Detail of interstice

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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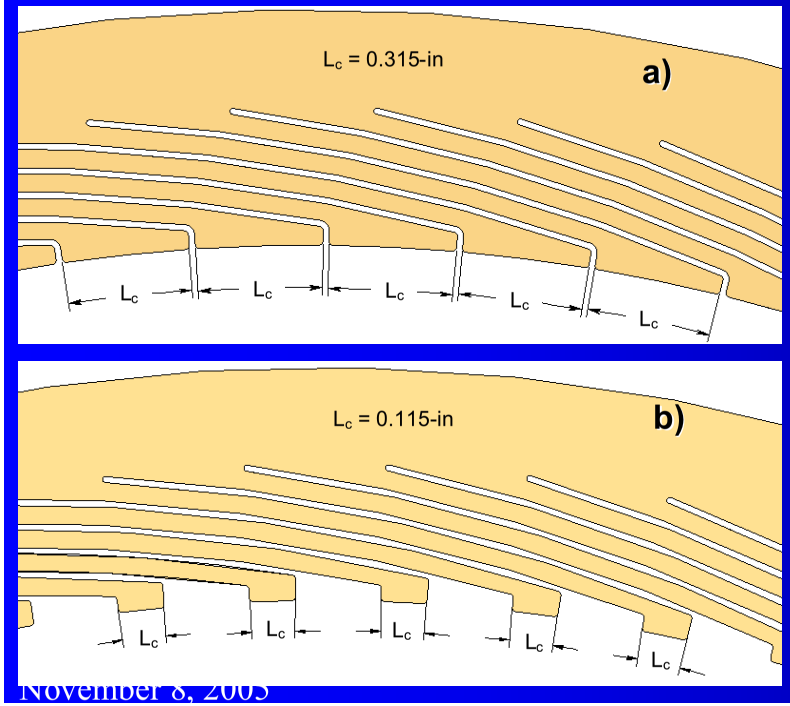
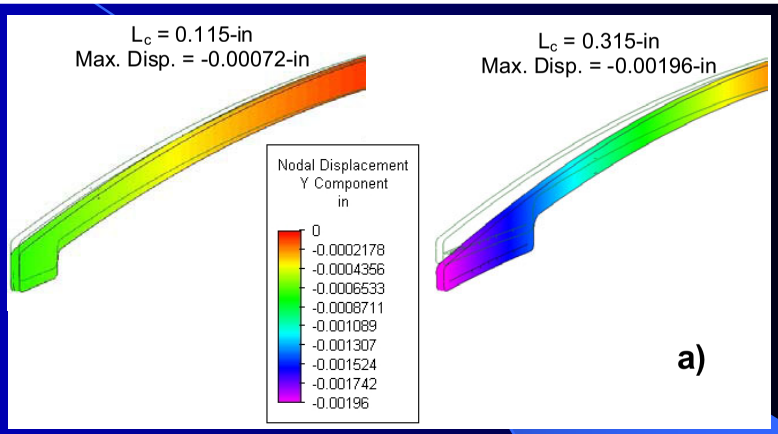
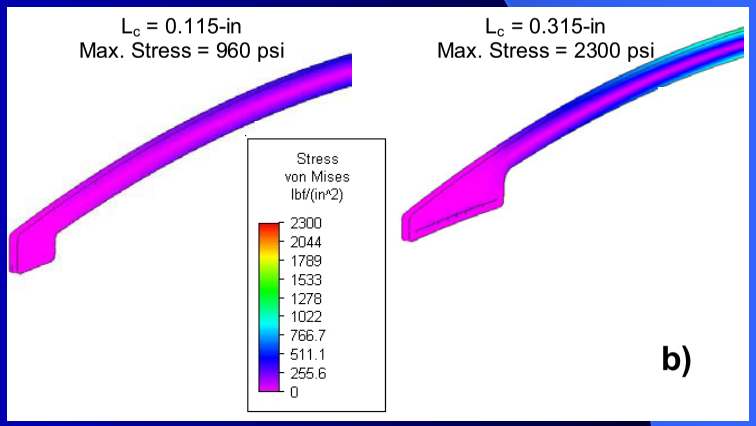
(7) L_c Circumferential Foot Length.

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







Resultant Contours Comparisons for a Change in Lc to 0.115-in from 0.315-in: (a) Deflection Dither, (b) Stress Dither

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

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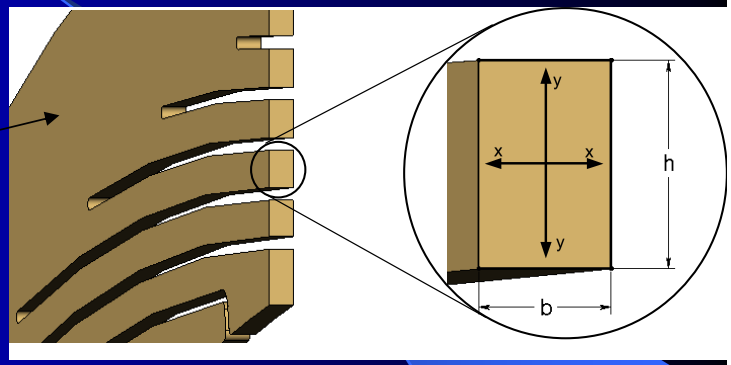
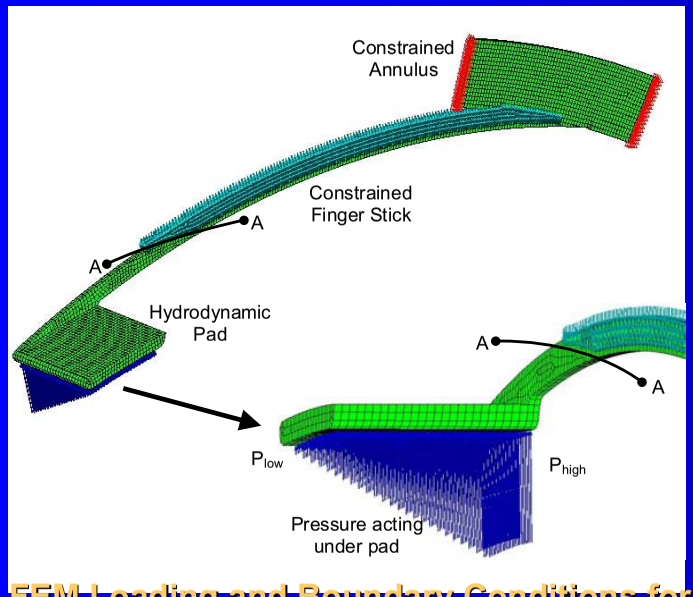
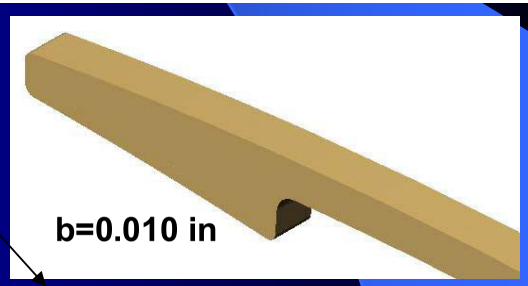
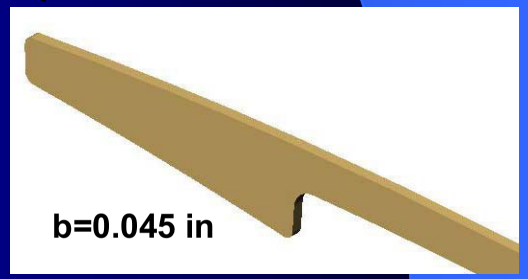
(8) b-Laminate thickness.

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_{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

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

Variations in Finger Pad Design

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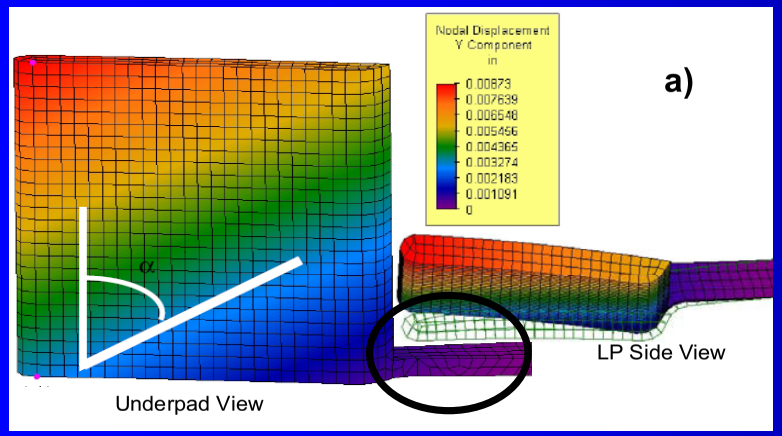
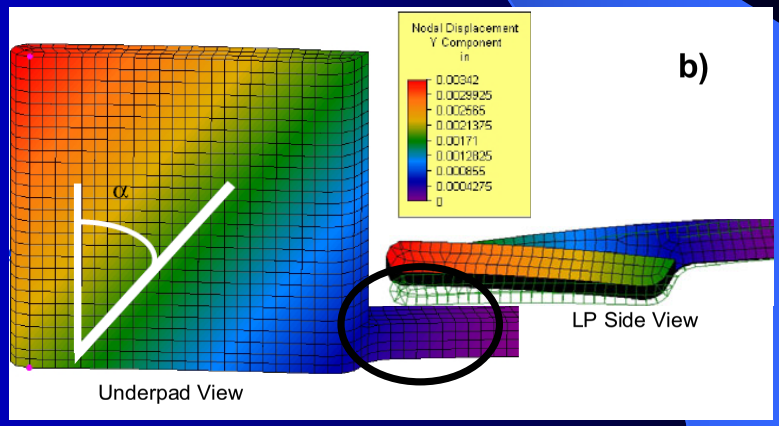
The finger seal obtains its hydrodynamic lifting capabilities from the pattern of the padded fingers underside, which "rides" the surface of the shaft. The objective in the design of the pad was to determine an optimal configuration that would enable the pad portion to lift from the rotating rotor and 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

DESIGN PARAMETERS (cont'd)

(Variations in the Design of the Finger Stick and Foot)

Variations in Finger Pad Design

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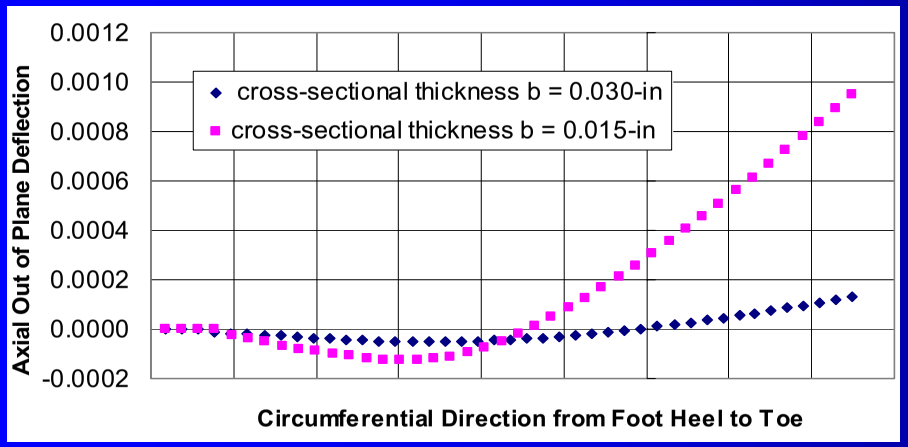
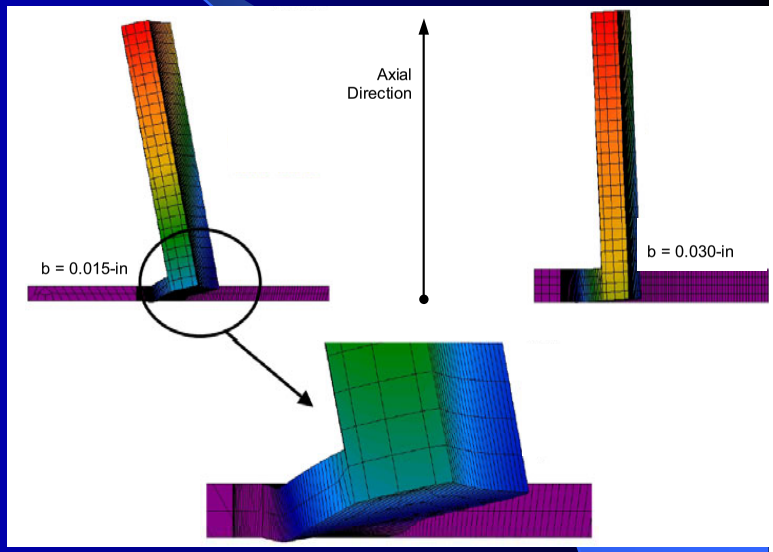


Shape of the underpad surface Axial Out-of-Plane Twisting for Stick Thickness of b=0.015-in and b=0.030-in



Another view of pad and stick deformation

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

x-, y- and z- Displacements

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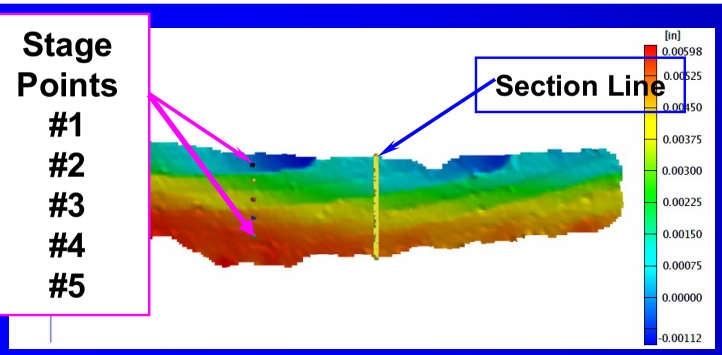
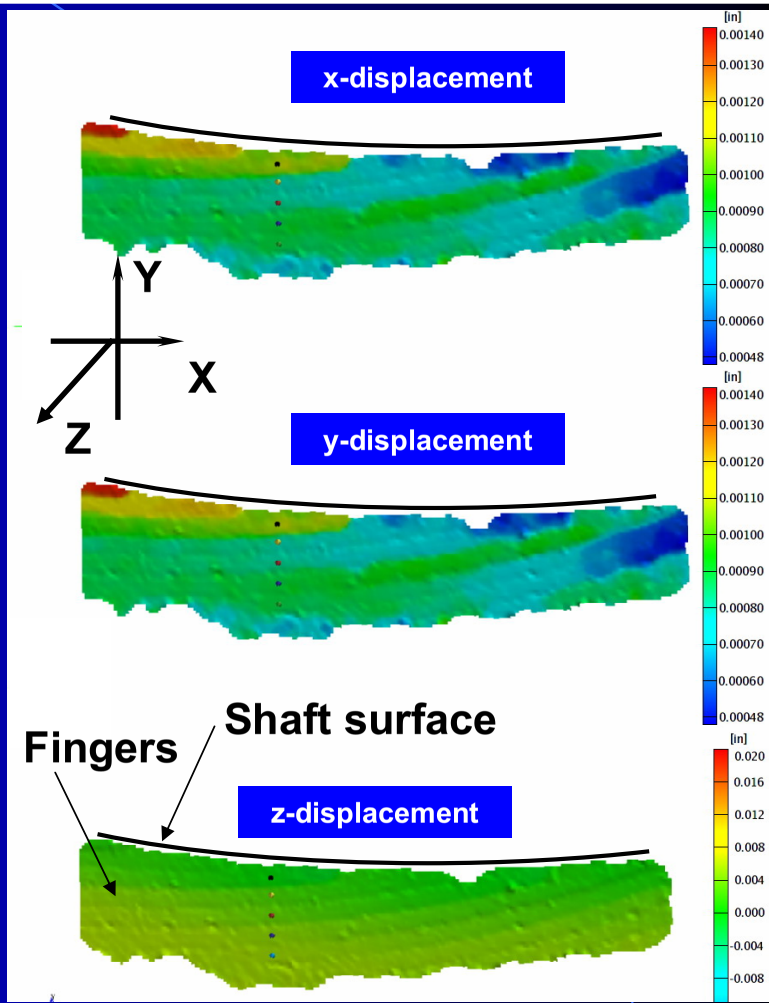
Stage Points
#1
#2
#3
#4
#5



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

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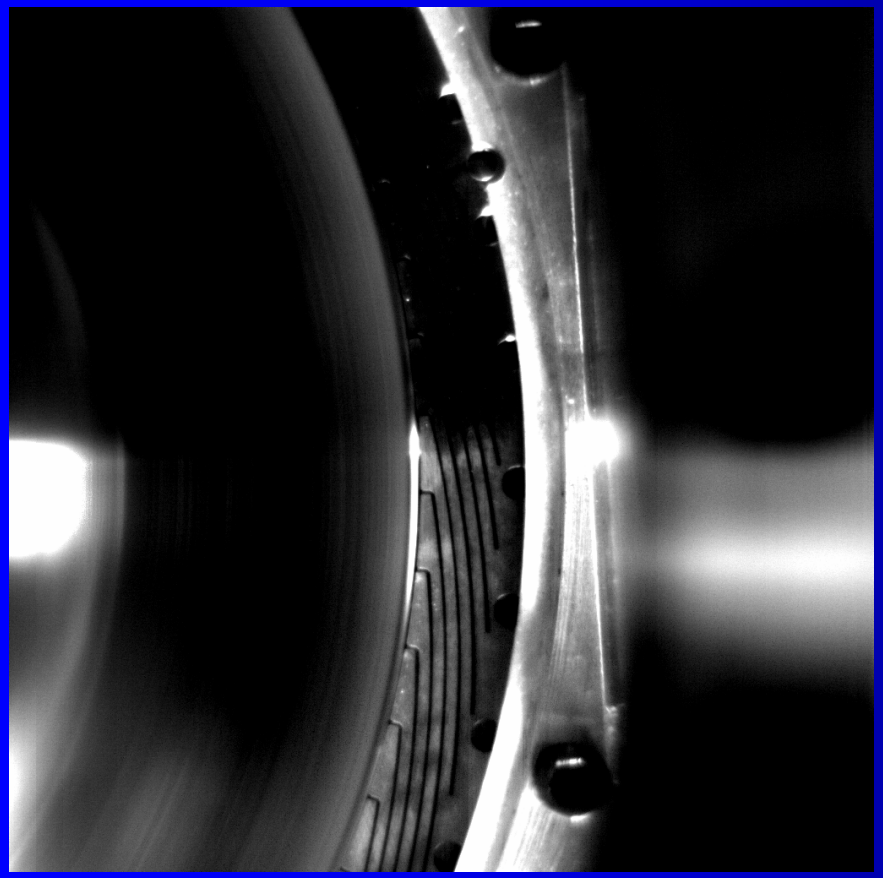
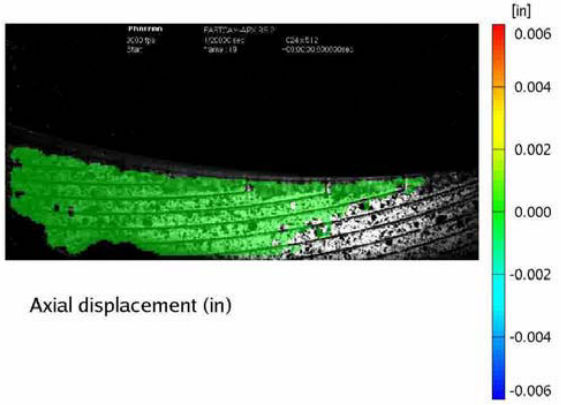
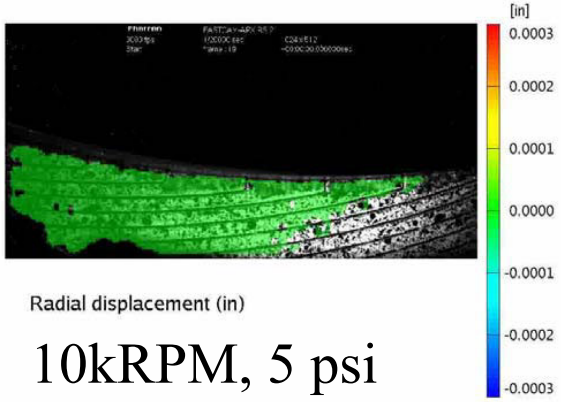


10,000 RPM



Axial displacement (in)



Radial displacement (in)

10kRPM, 5 psi

The University of Akron

November 8, 2005

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

Time History Displacement of The Stage Points

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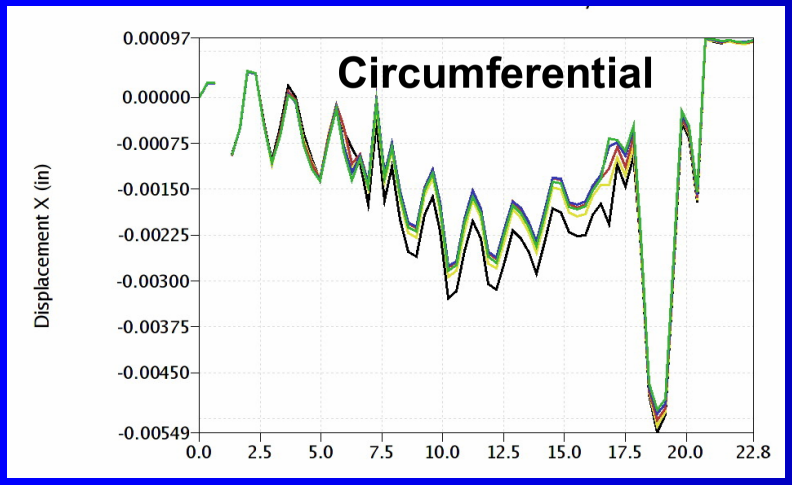

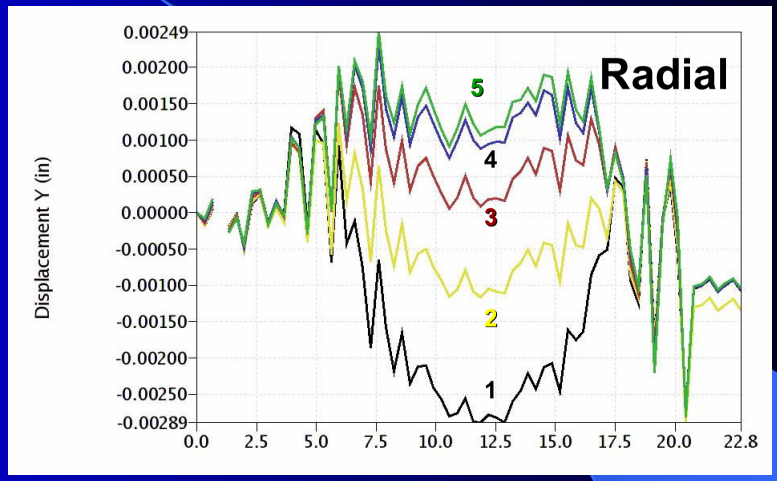

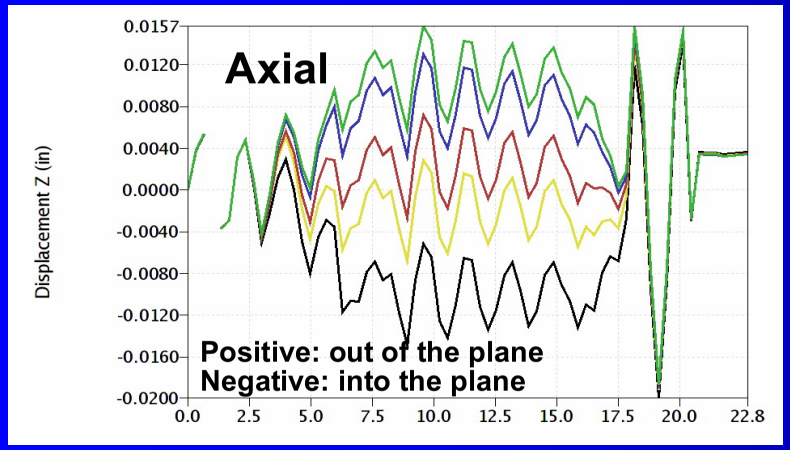

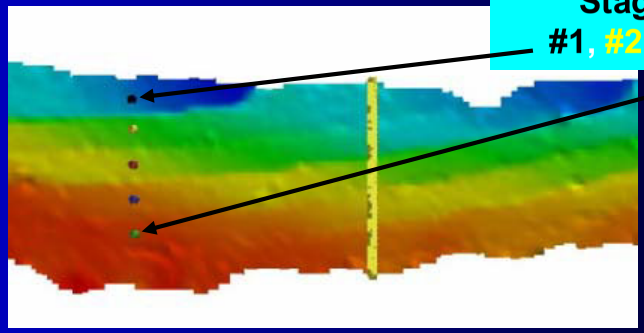

The color of the stage points # corresponds to the color of the curves above

November 8, 2005

CONCLUDING REMARKS (1)

Finger Behavior with Rotating Shaft and Axial Pressure Differential

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- 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

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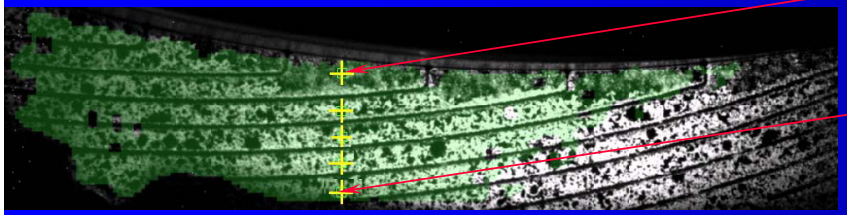

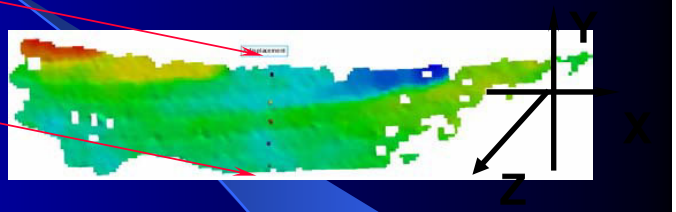

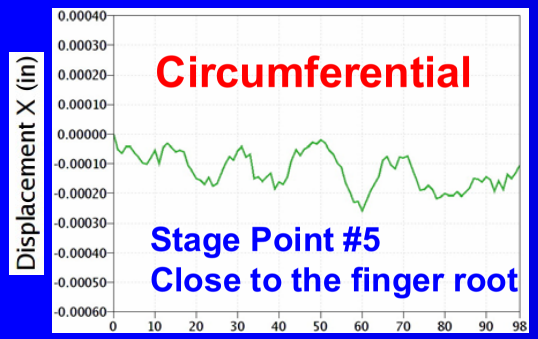

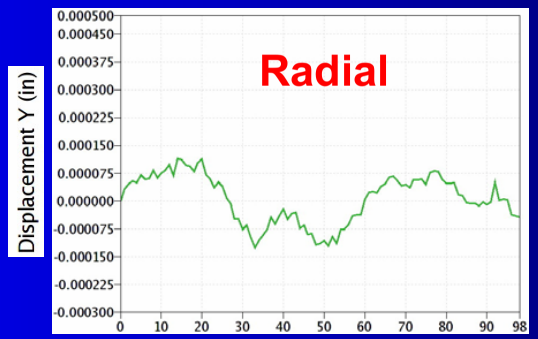

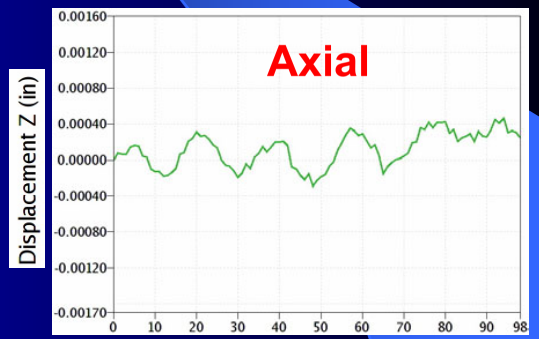

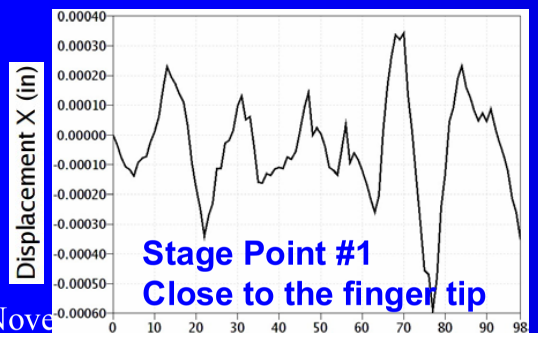

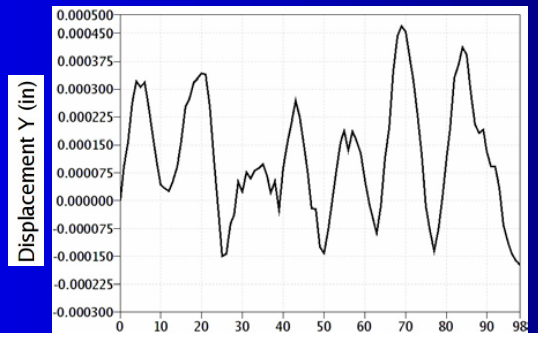

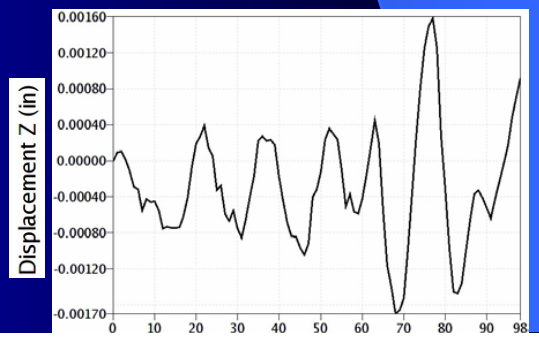

Nove

CONCLUDING REMARKS (2)

Finger Behavior with Rotating Shaft and No Axial Pressure Differential

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- 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,

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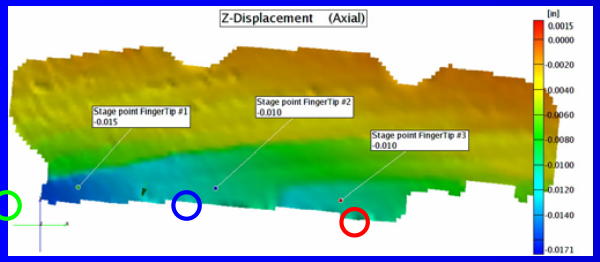
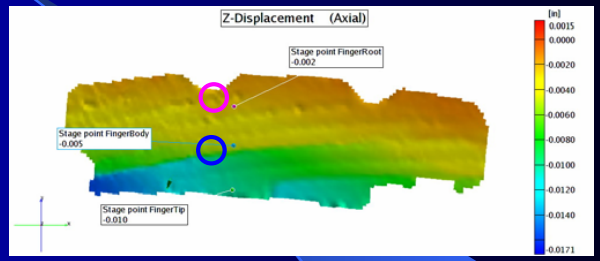
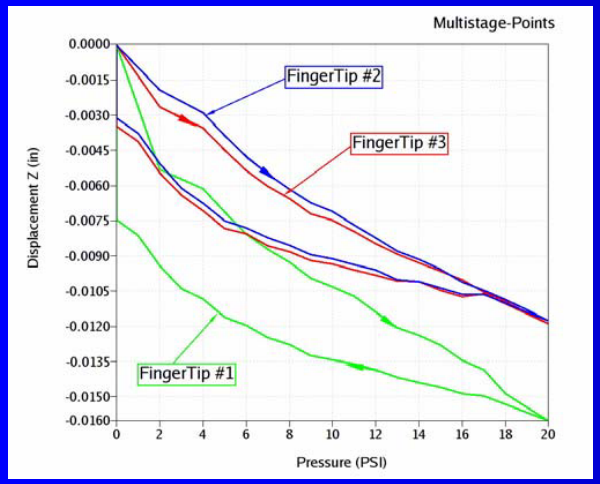
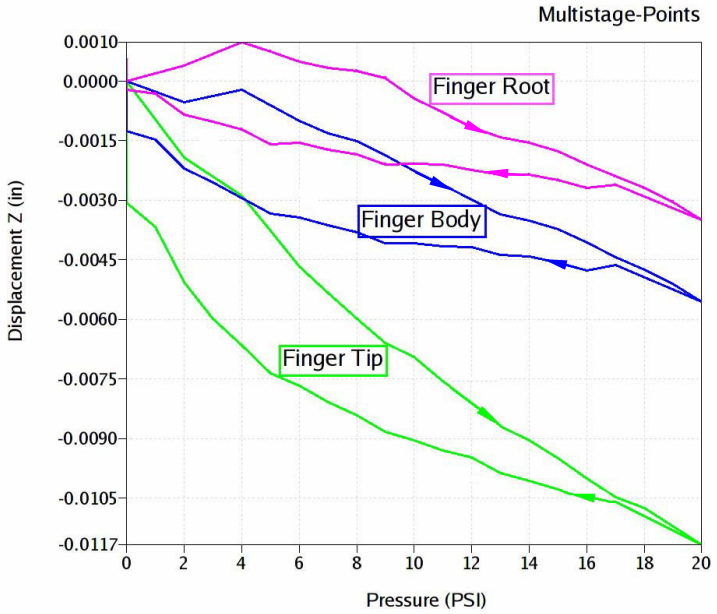






From initial state, pressure was increased from 0 to 20 psi and then decreased to 0 psi. The test was to investigate the finger behaviors under such a pressure shock



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CONCLUDING REMARKS (3)

Finger Behavior with Axial Pressure Differential, No Shaft Rotation.

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- With axial pressure drop only , all the finger moves 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 shows sharp jump between the fingers, which indicates that they cam move independently.

COMPUTATIONAL GRID

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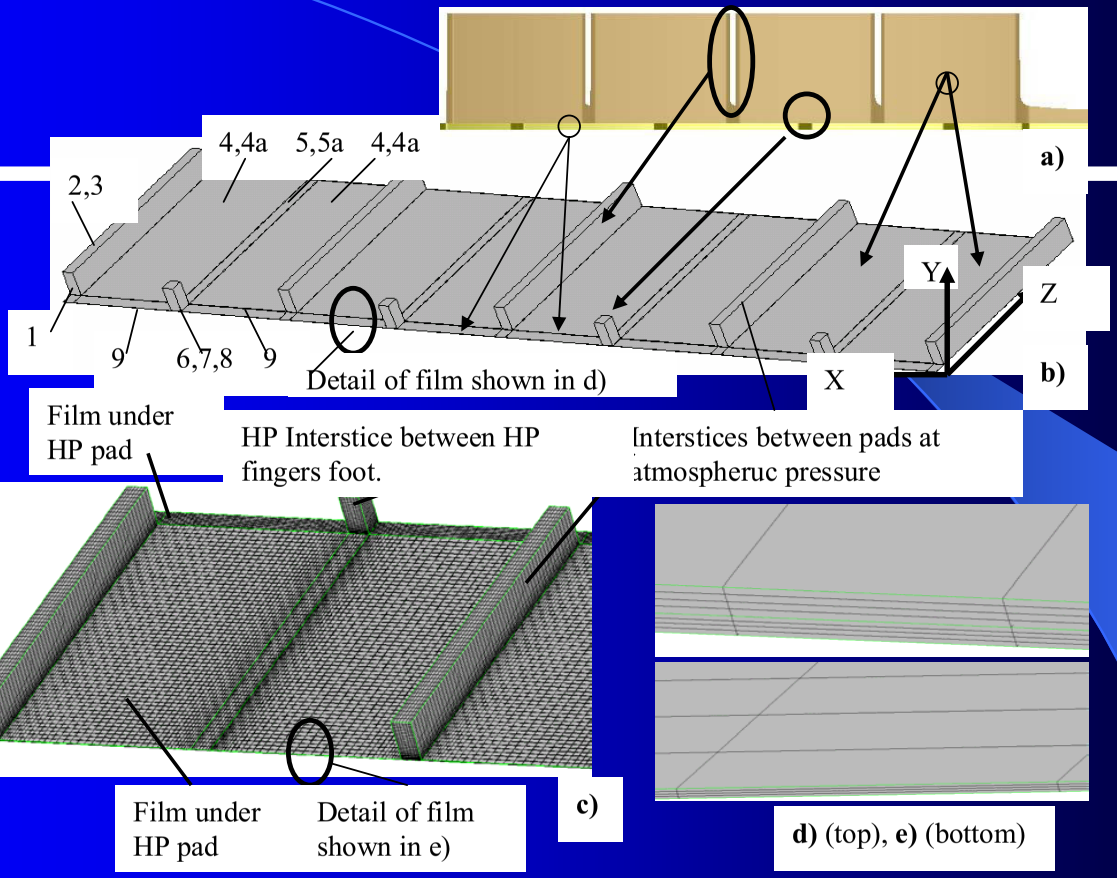

Grid Details for the Pressure, Flow and Temperature Calculations.
a) Solid representation of the two rows of fingers viewed from below
b) Corresponding representation of the fluid film contained between the rotor and the assembly of fingers.
c) Detail of the cell structure in the fluid film below and in-between HP and LP pads.
d) Fluid film grid structure under the HP finger
e) Fluid film grid structure under the LP finger

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General 3-D Flow Paterns

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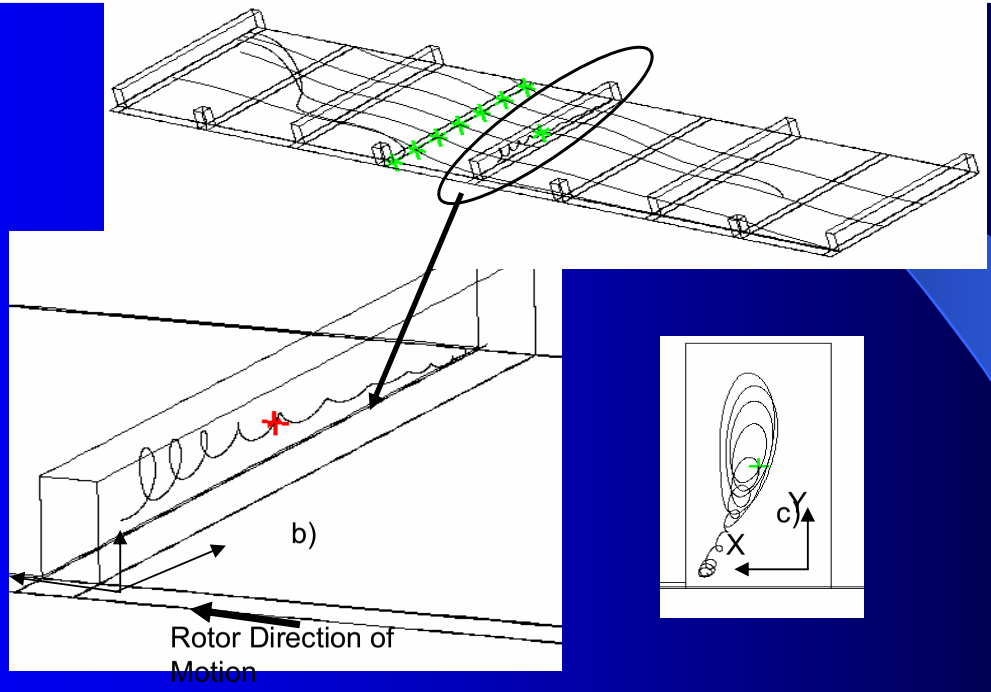

Flow trajectories visualized with individual 4-finger cell showing circumferential flow. a) tracers showing circumferential flow; b) 3-D flow between low pressure fingers, c) frontal view of flow in b)

THERMOFLUID BOUNDARY CONDITIONS

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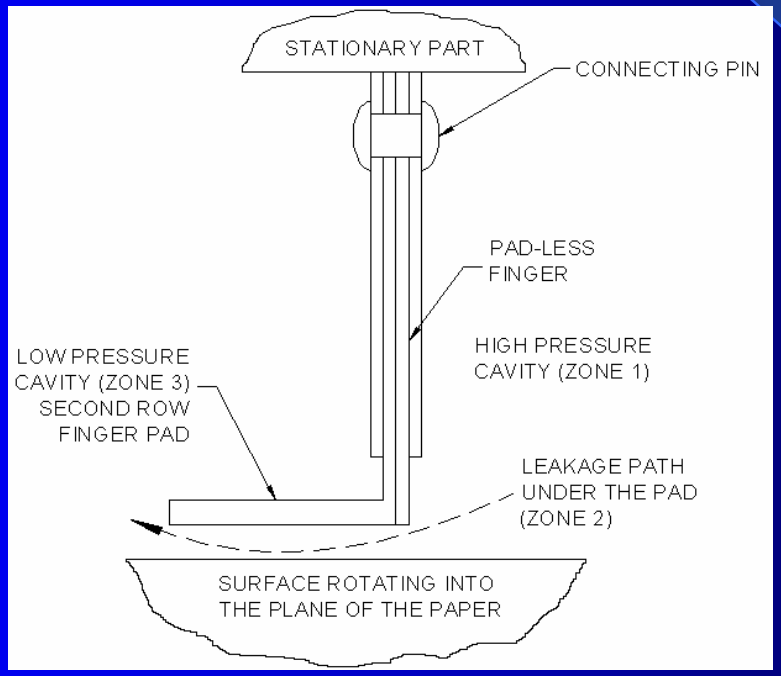

Boundary conditions for the Finger Seal. Schematic Cross Section with Two Rows of Padded Low- and Pad-less High Pressure Fingers

PRESSURES: INCOMPRESSIBLE vs. PGL

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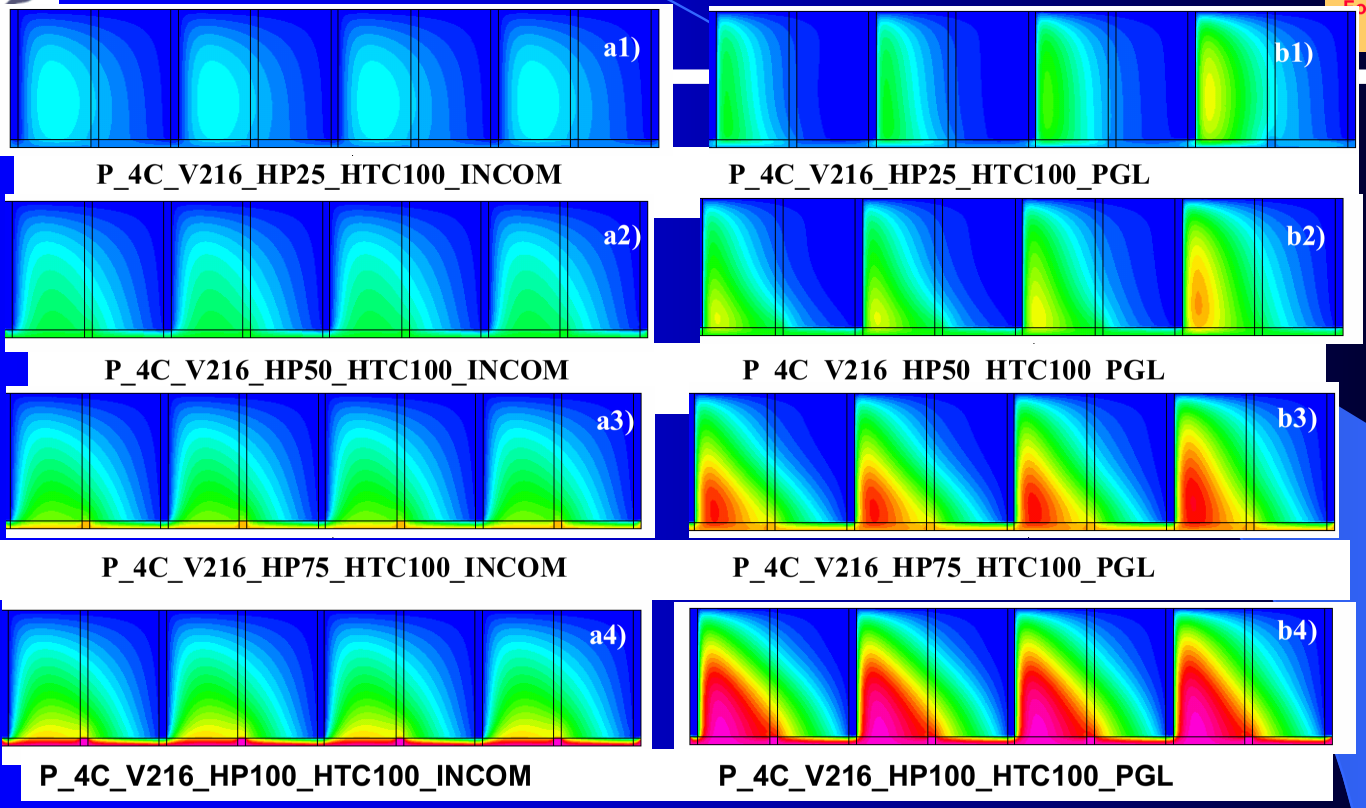

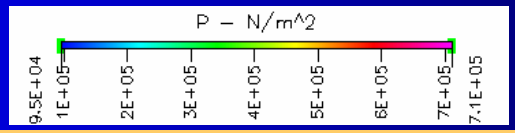

Comparison between pressure magnitude development under the fingers when incompressible(ρ ,μ=const) and perfect gas laws are used.

TEMPERATURES: INCOMPRESSIBLE vs. PGL

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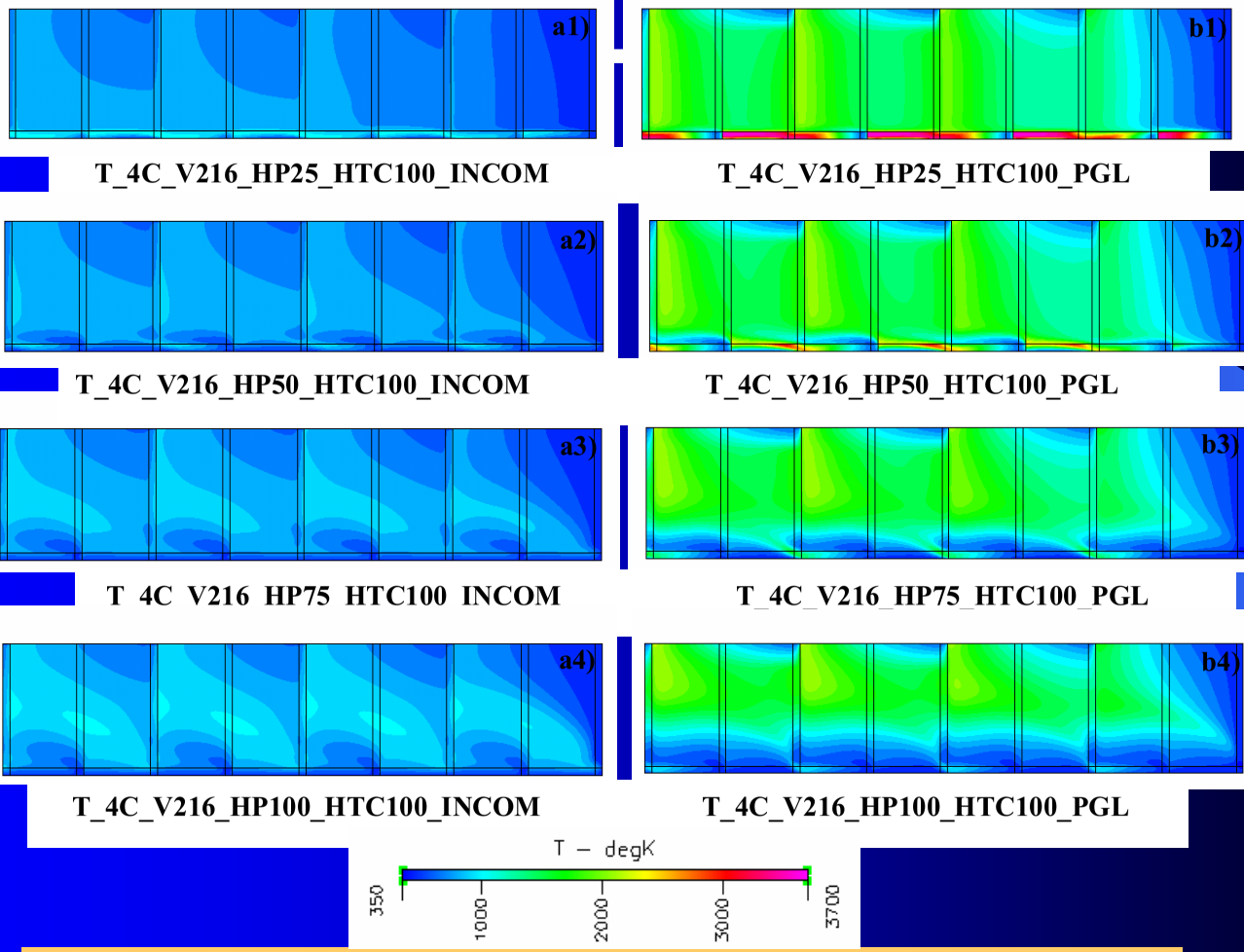

Comparative temperature map for the incompressible and perfect gas law cases. The adiabatic case.

PRESSURES: ISOTHERMAL
216 m/s and 432 m/s

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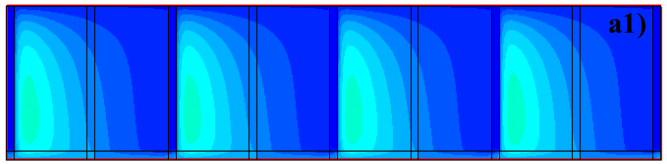
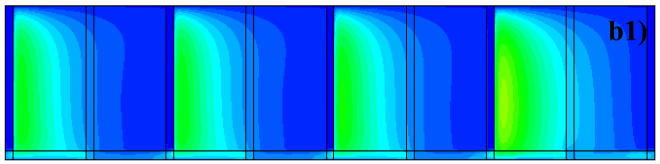


P_4C_V216_HP25_HTC1000_PGL



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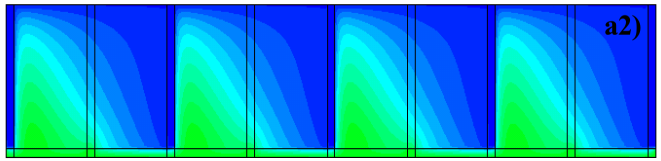
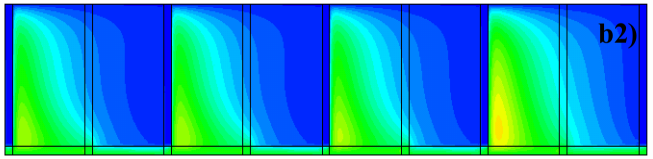
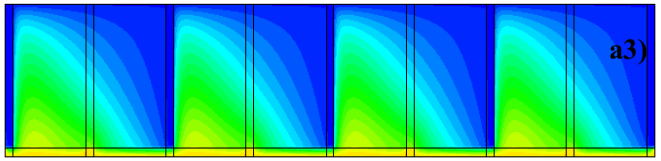


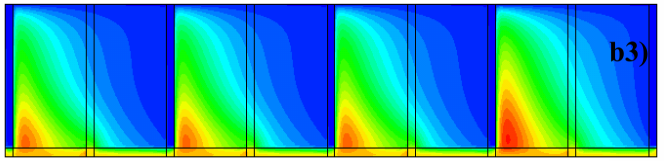
P 4C V216 HP50 HTC1000 PGL



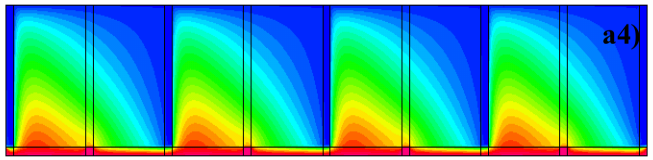
P_4C_V432_HP50_HTC1000_PGL



P_4C_V216_HP75_HTC1000_PGL



P_4C_V432_HP75_HTC1000_PGL



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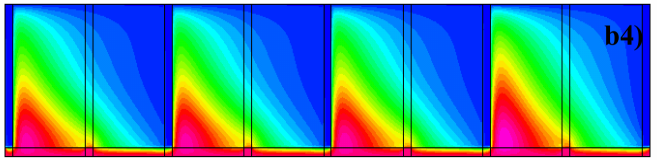

P_4C_V432_HP100_HTC1000_PGL

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

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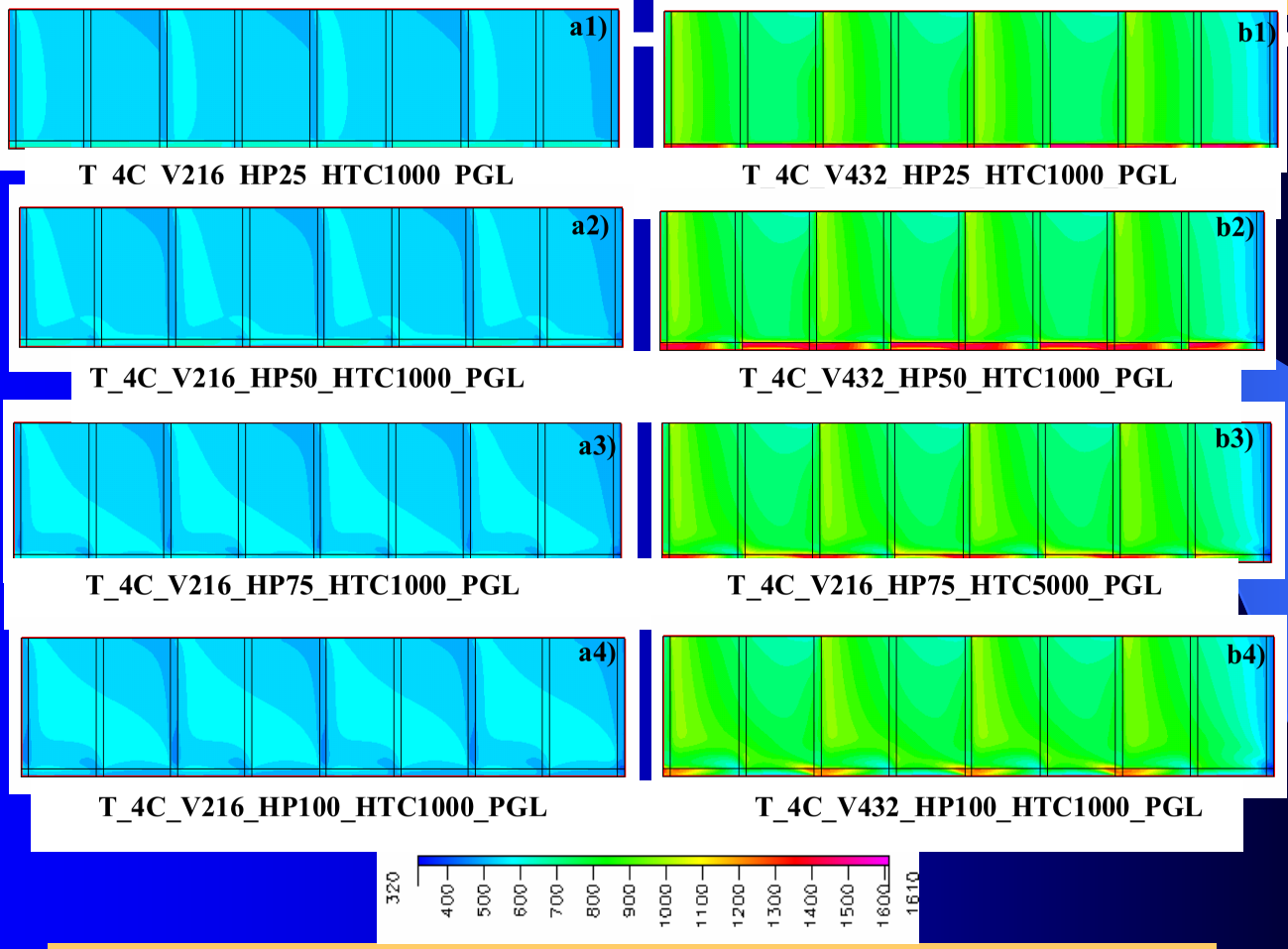

Temperature development when the angular velocity is varied from 216 m/s linear, to 432. The almost isothermal case.

Single Finger Geometry (Solid-Fluid Interaction)

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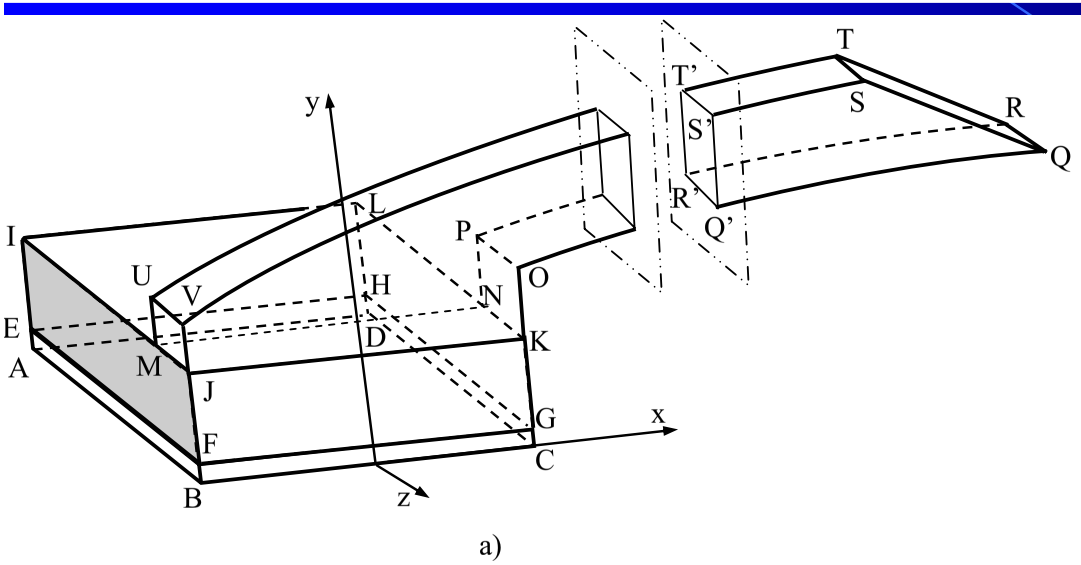
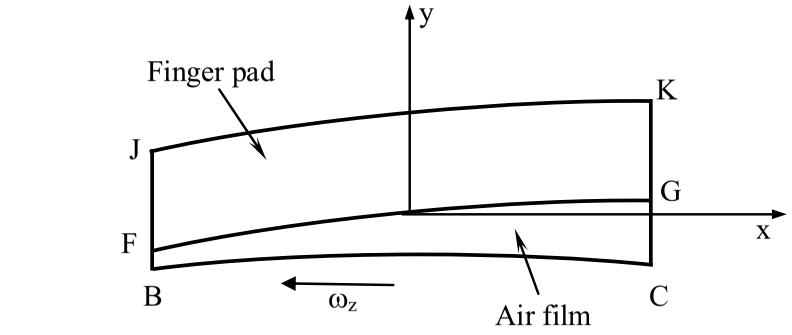
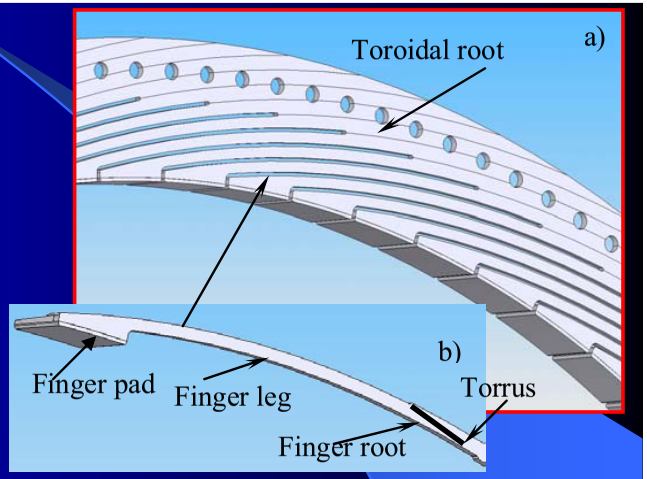


a)



b)



Moving Finger

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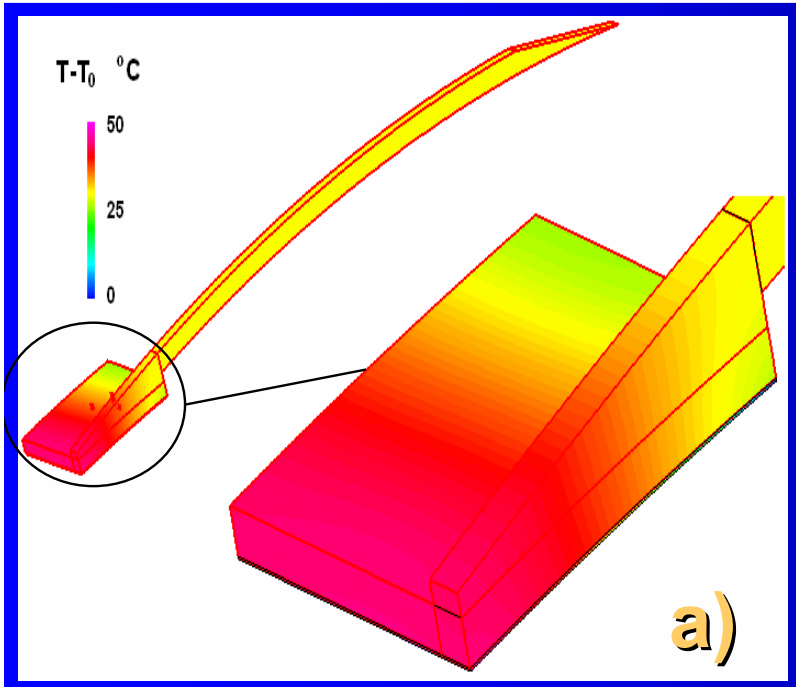

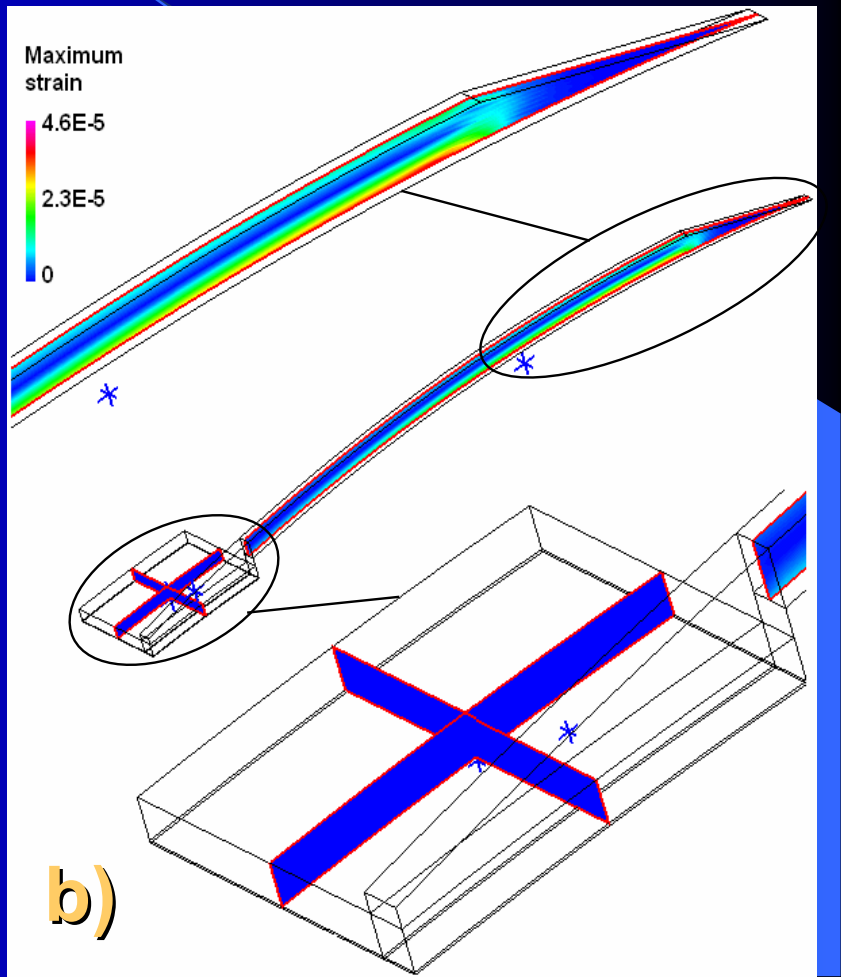

Temperature (a) and strain (b) in the finger pad and leg. Adiabatic conditions on finger and rotor surfaces.

Rotor rotates at 30000 rpm

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Lift of the pad central section with angular velocity

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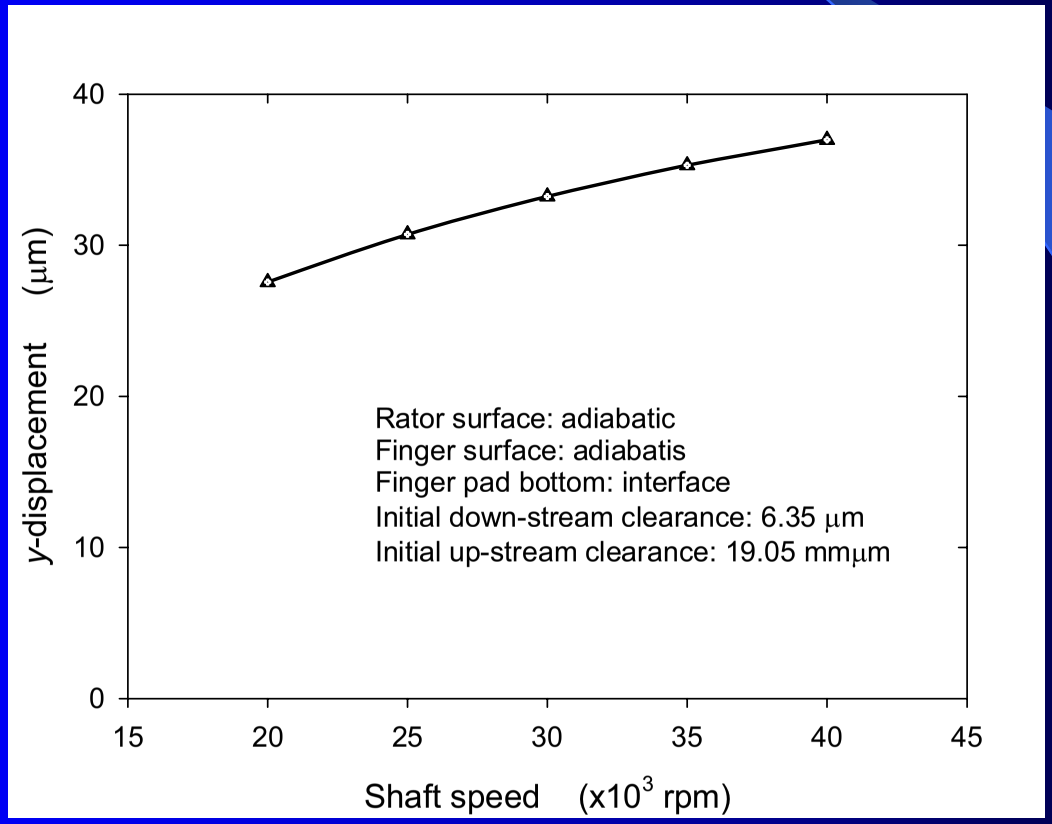

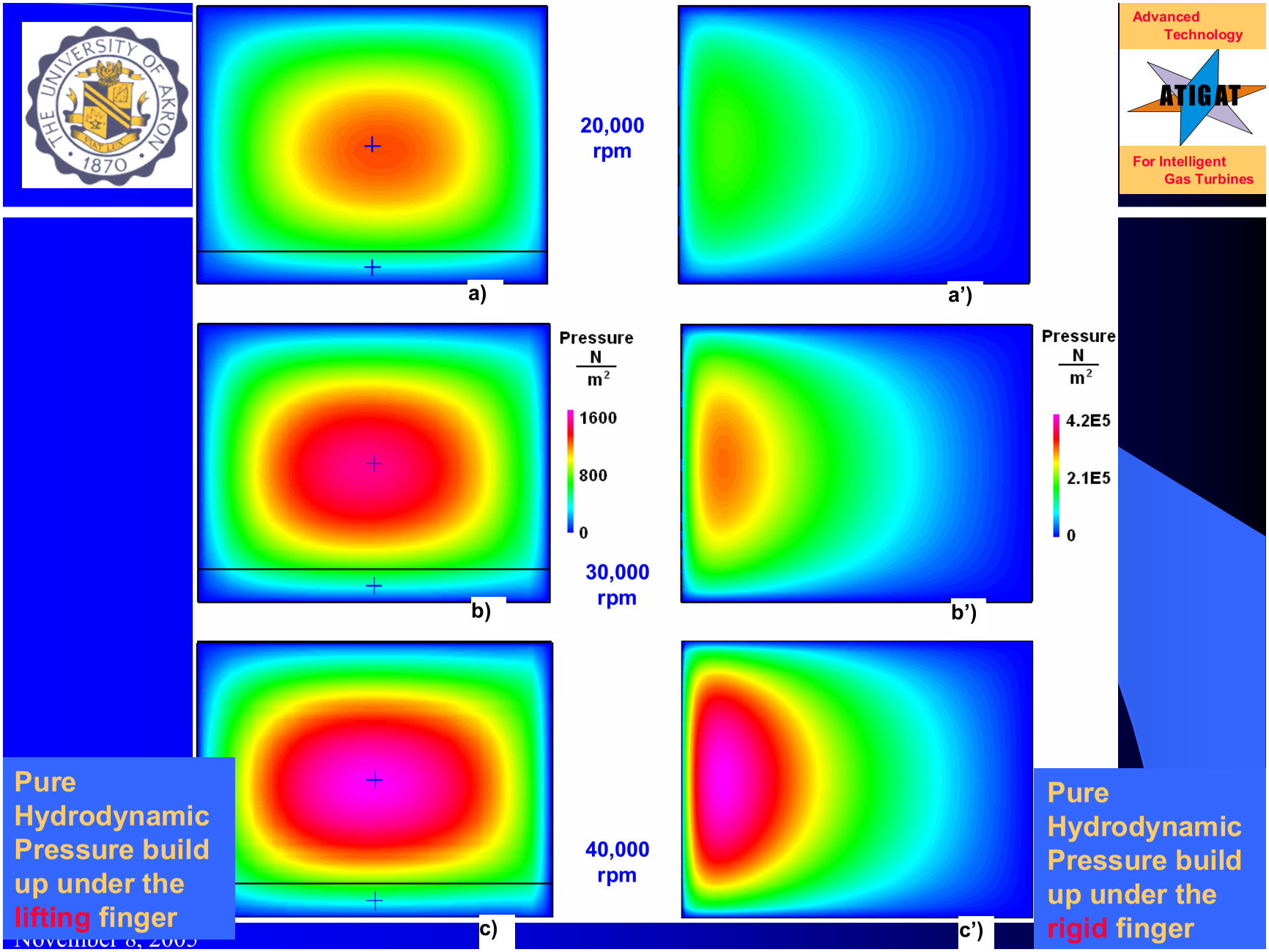
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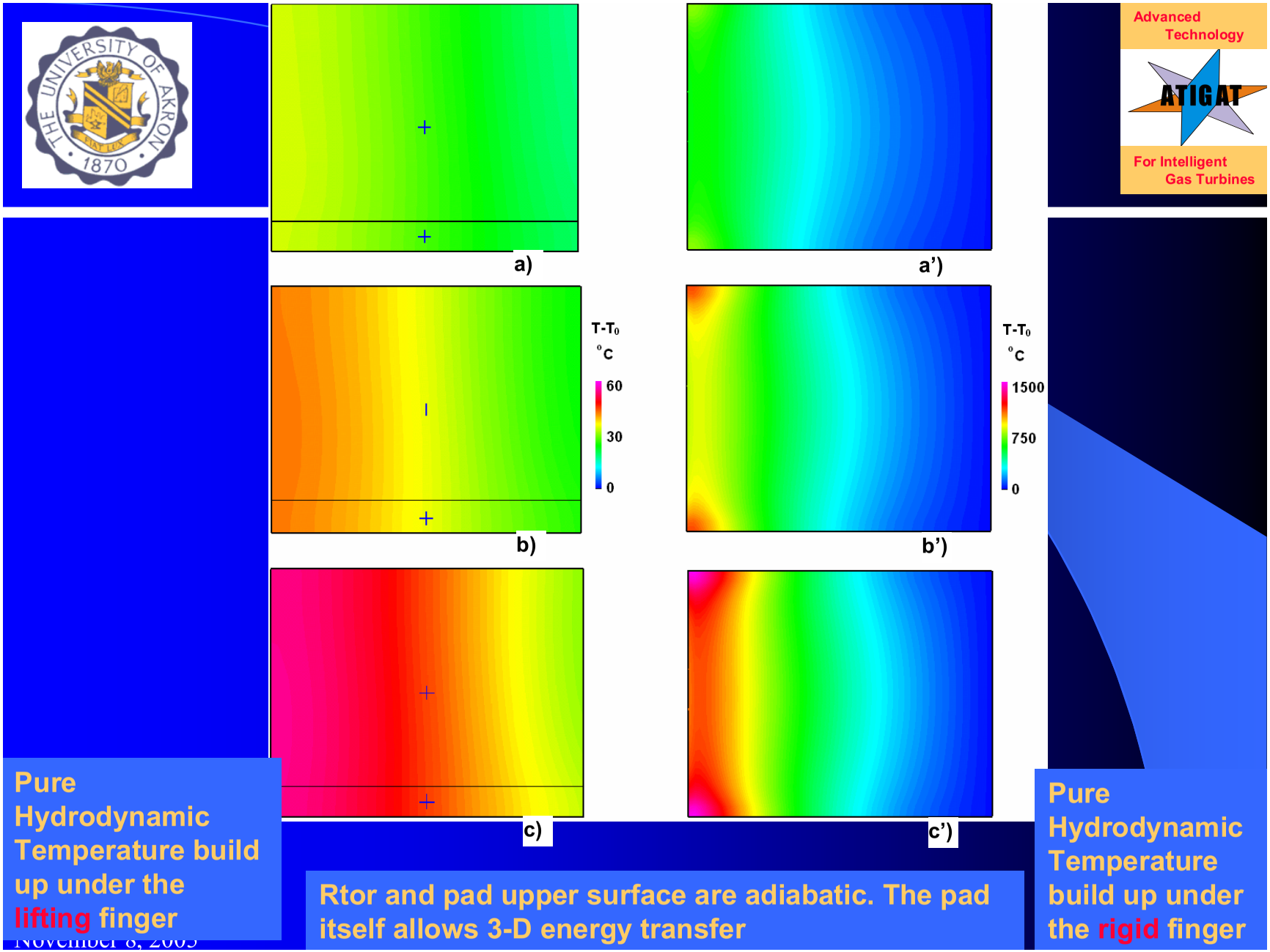
20,000 rpm
30,000 rpm
40,000 rpm
a)
a')
b)
b')
c)
c')
Pressure N/m²
1600
800
0
4.2E5
2.1E5
0
Pure Hydrodynamic Pressure build up under the lifting finger
Pure Hydrodynamic Pressure build up under the rigid finger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a)
a')
T-T0 °C
60
30
0
b)
b')
T-T0 °C
1500
750
0
c)
c')
Pure Hydrodynamic Temperature build up under the lifting finger
Rtor 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

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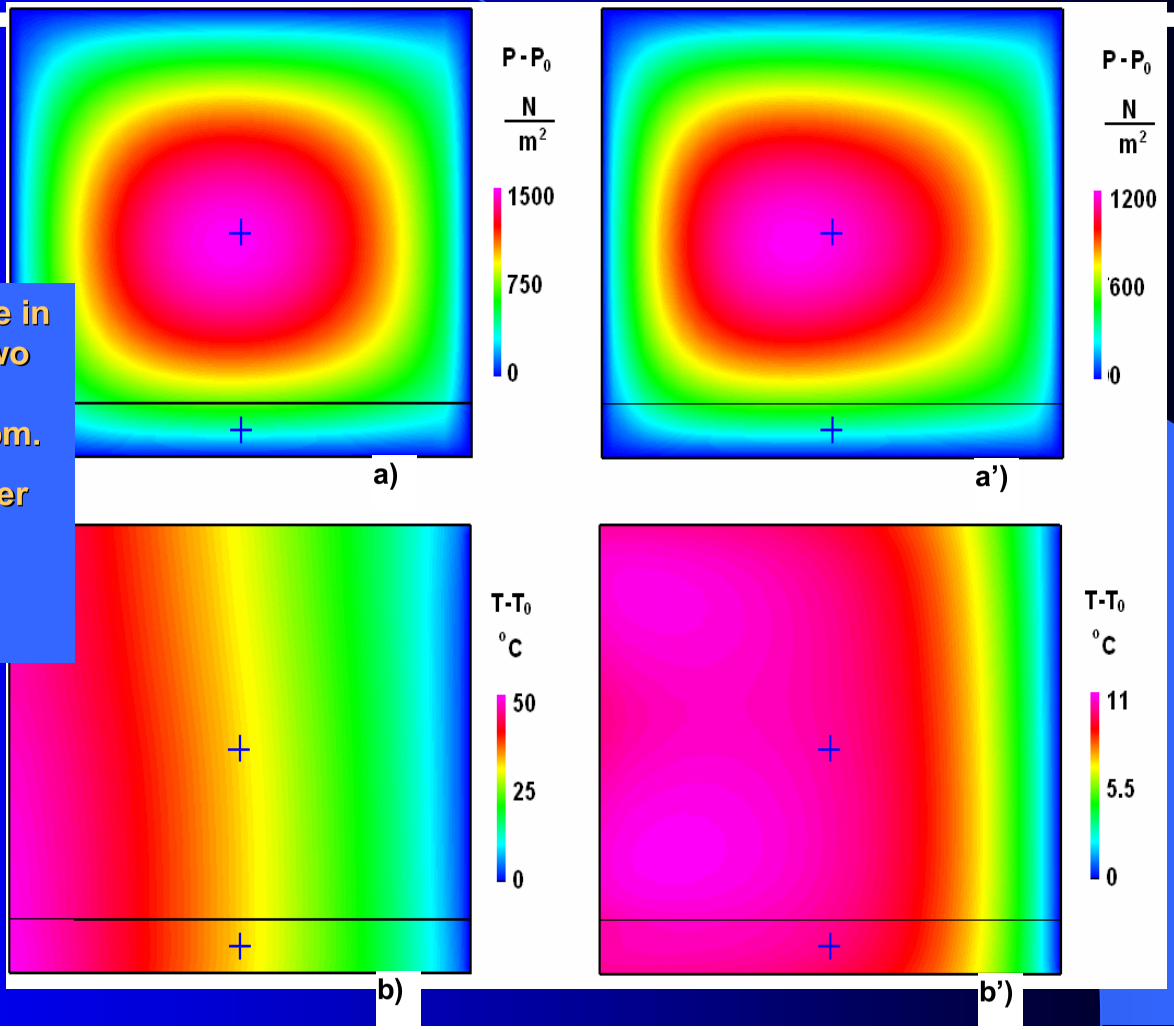
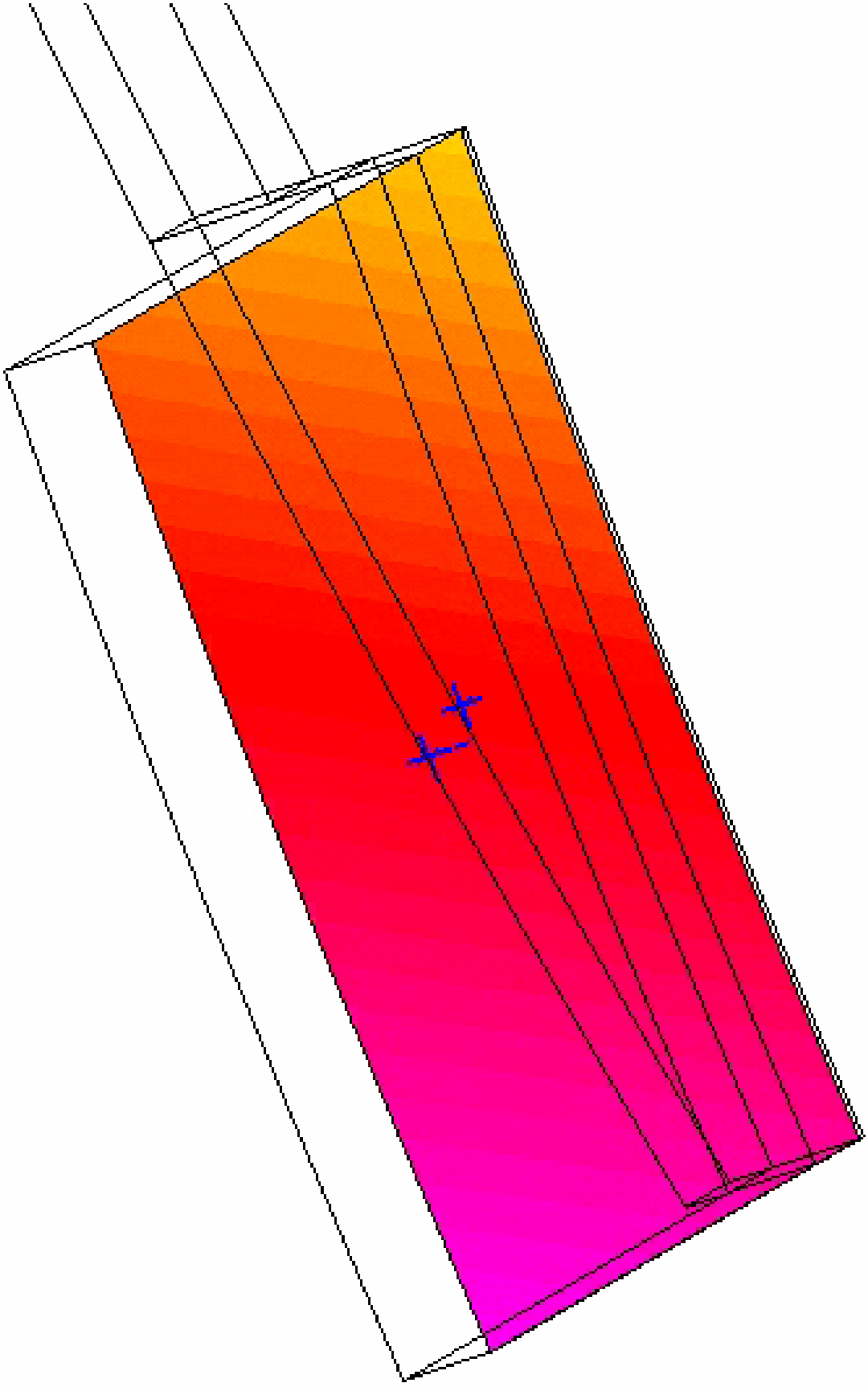
The pressure and temperature in the center of the air film for two thermal boundary conditions with rotor rotating at 30000 rpm.

(a, b) Adiabatic rotor and finger surfaces.

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





EQUIVALENT DYNAMIC MODEL

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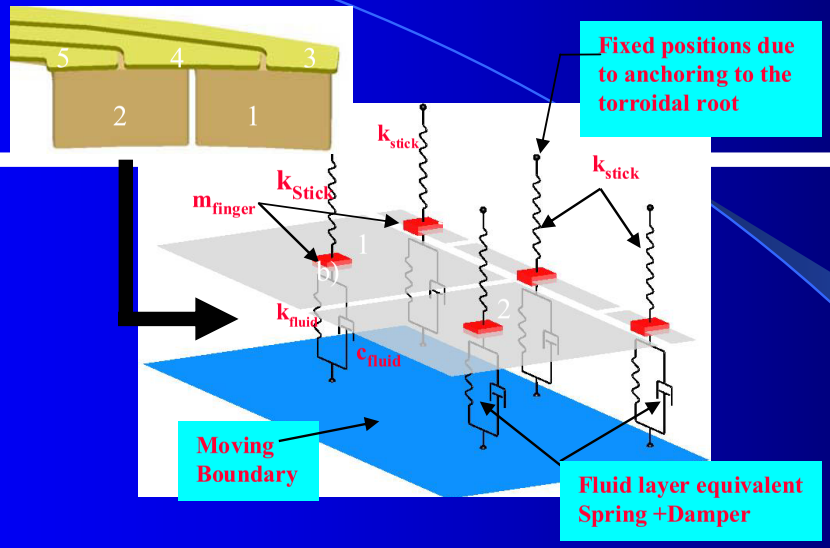
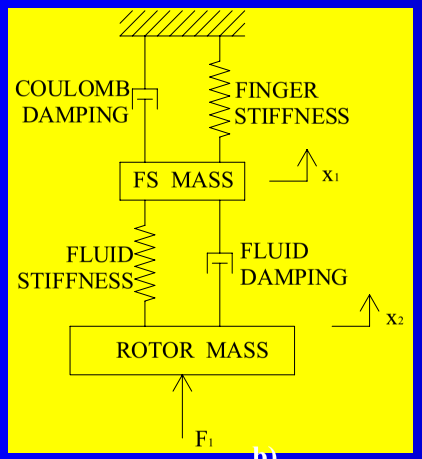
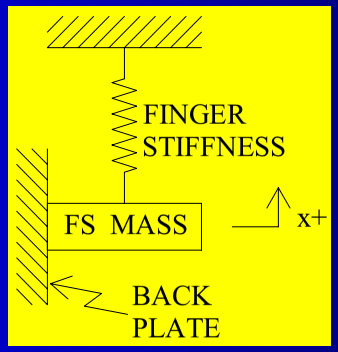


a)



b)



c)

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

FINGER DYNAMICS-2
Free Vibration
Stiffness is varied

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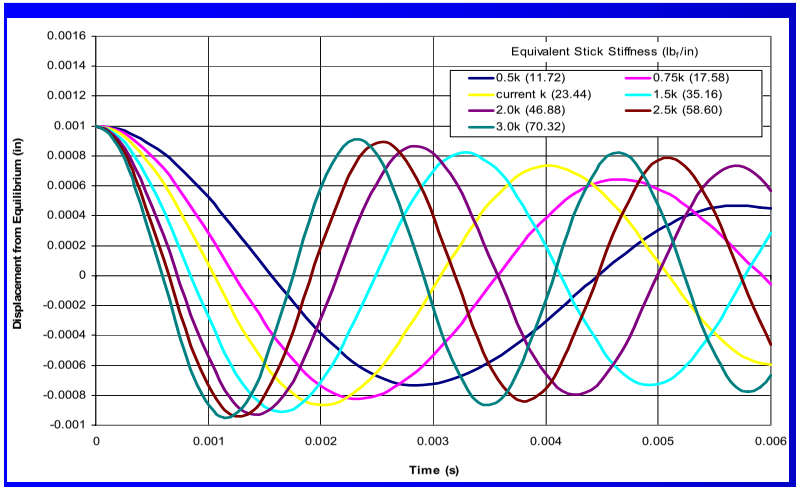
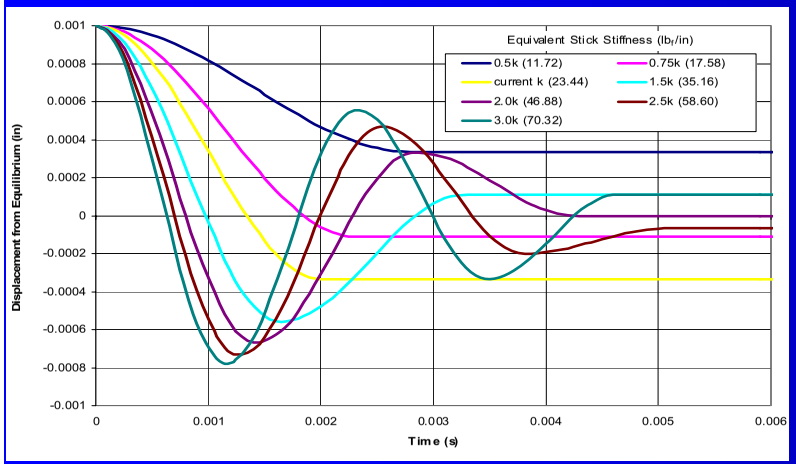
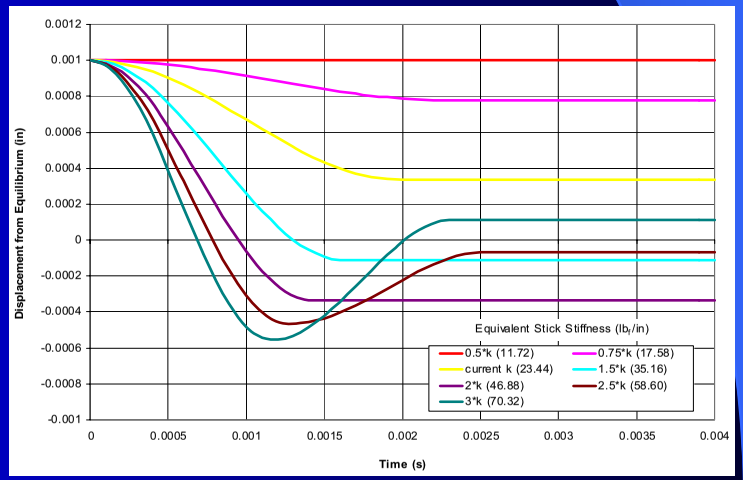


a)



b)

Finger assembly free vibration when k_{SEqu} is varied: a) Δp_C=6.9 kPa (1psi); b) Δp_C=34.5 kPa (5psi); c) Δp_C=69 kPa (10psi);



c)

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FINGER DYNAMICS

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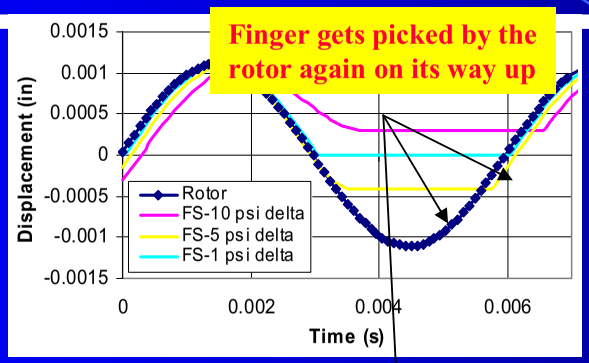

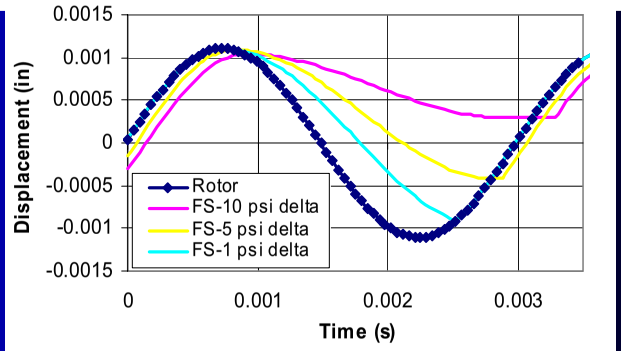

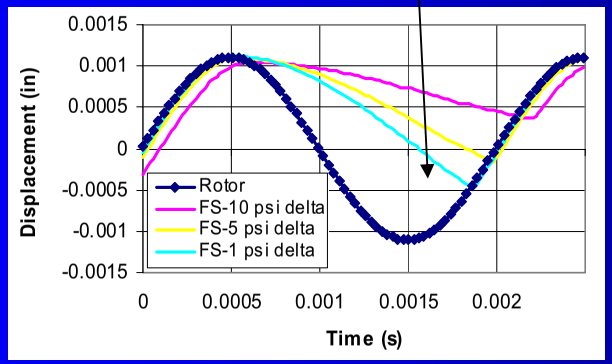

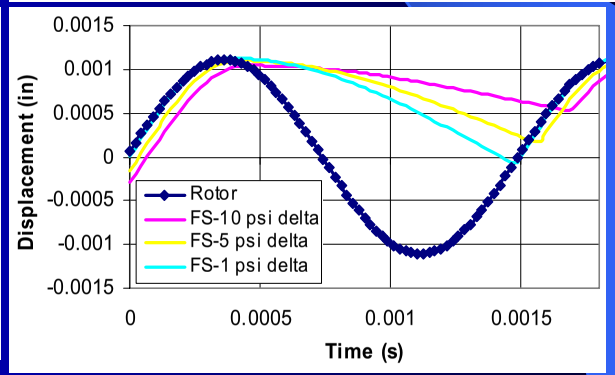

Finger following the rotor when Coulomb damping force and rotor angular velocity is varied. Finger stiffness is

$$k_{SEqu} = 3.58\frac{N}{m}(20.44\frac{lbf}{in});$$

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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SOME EXPERIMENTAL WORK

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

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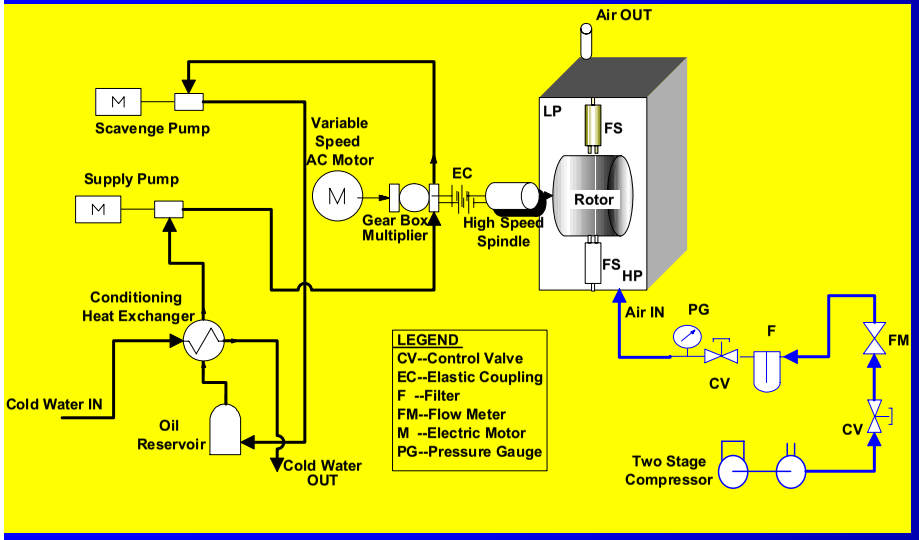

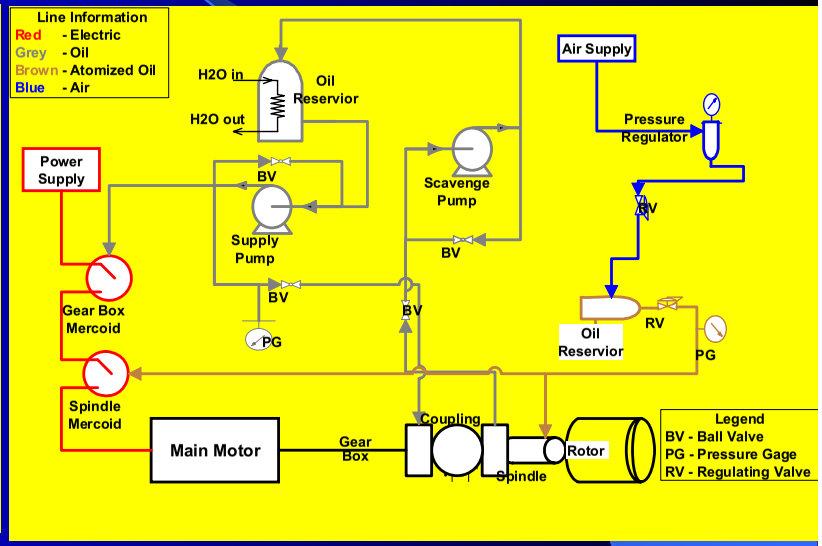

Overall inatallation

Electric, Oil and Air Circuits

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EXPERIMENTAL INSTALLATION

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Drive Train

Rotor Section

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ROTOR: FRONTAL VIEW

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Frontal view of the rotor.

ROTOR SURFACE

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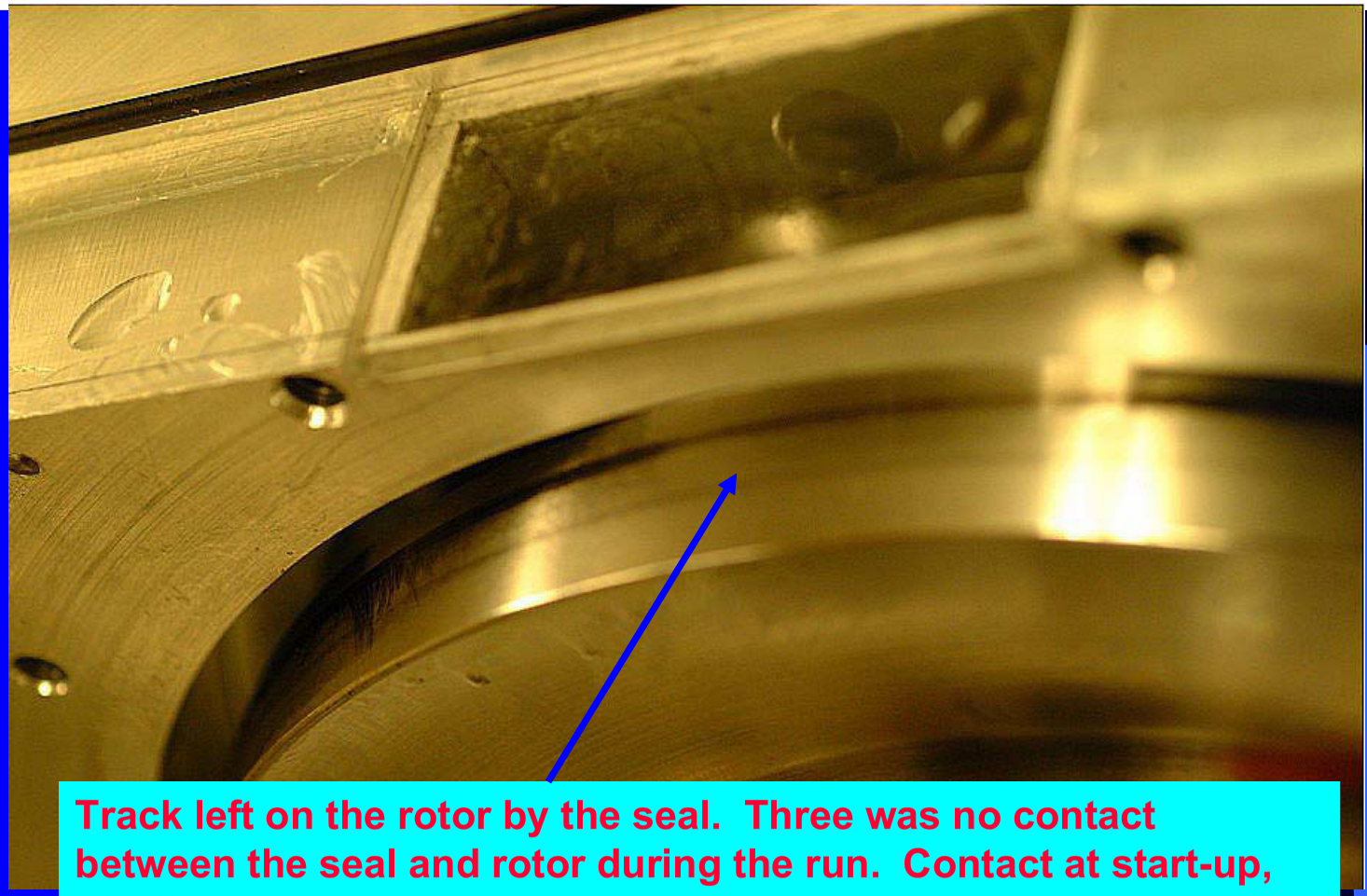

Track left on the rotor by the seal. Three was no contact between the seal and rotor during the run. Contact at start-up, liftoff-no contact, contact again at coast-down

FINGERS' PAD UNDERSURFACE

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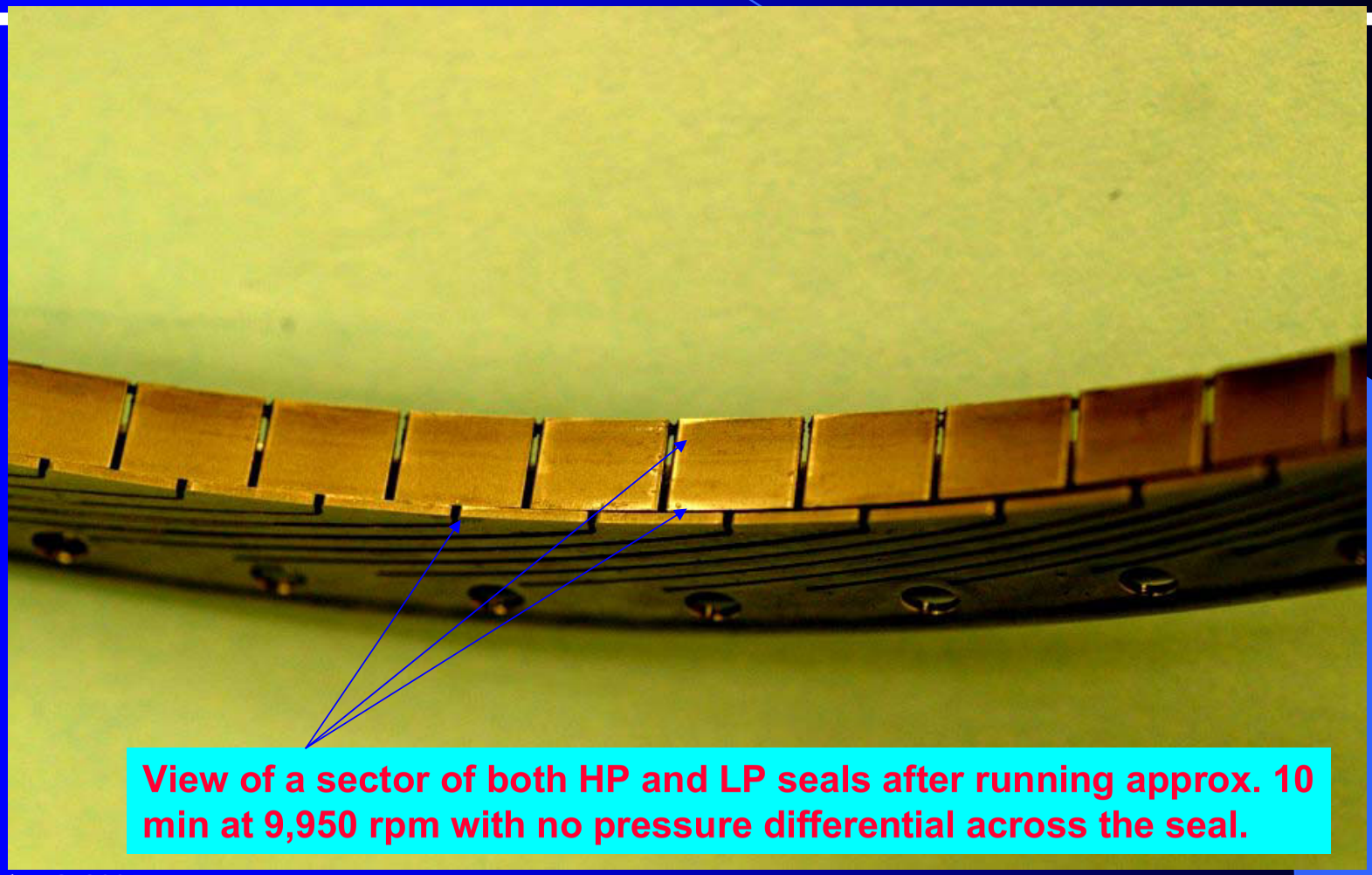

View of a sector of both HP and LP seals after running approx. 10 min at 9,950 rpm with no pressure differential across the seal.

FINGERS' PAD UNDERSURFACE DETAILS

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Enlarged view of two pads after the 10 min. run

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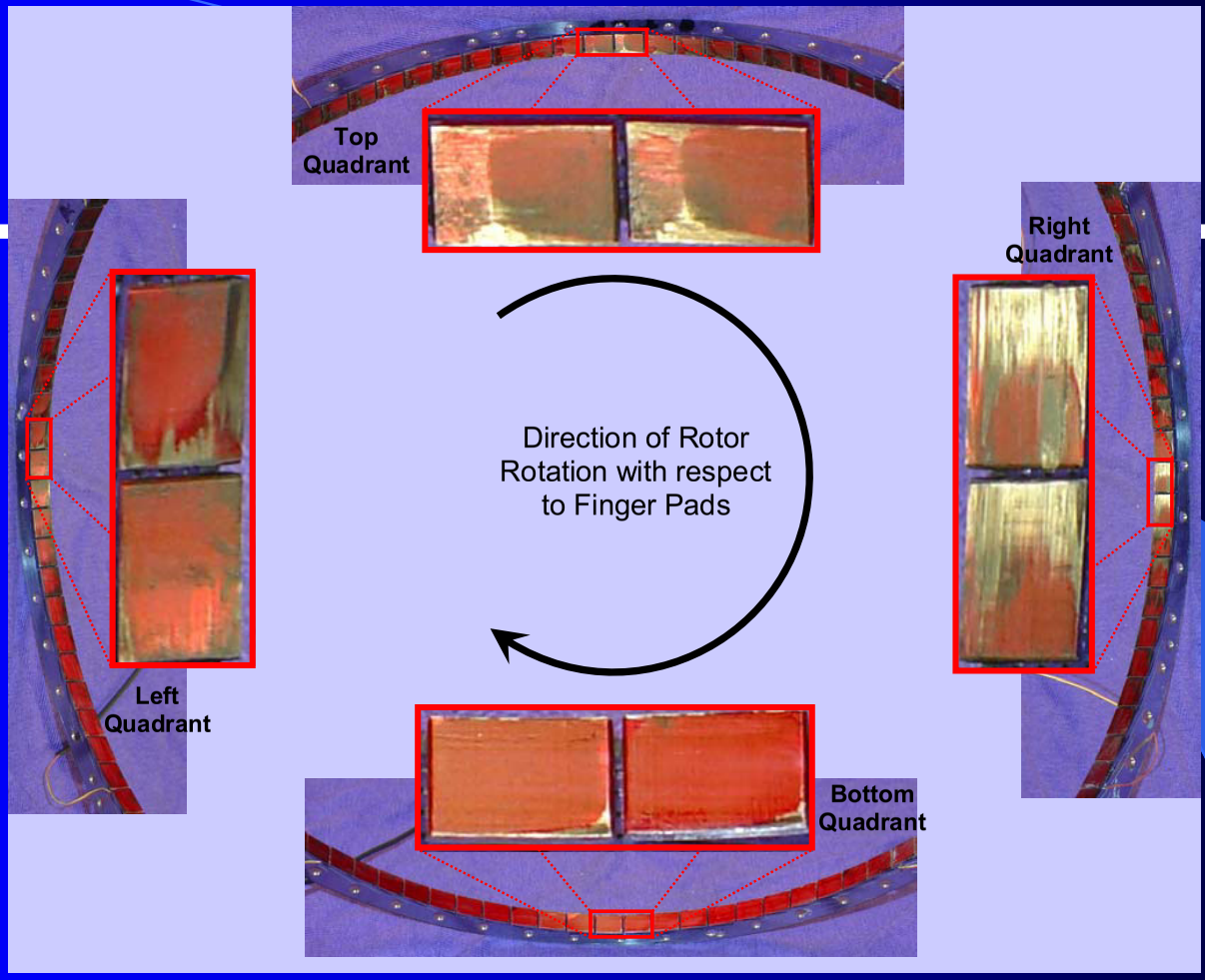

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LP Finger Underside Pads Surface Showing Ink Wear Marks after a Total Run Time of 97 min at a nominal speed of 9,950 rpm; This included 4 start-ups and 4 coast-downs. Seal Quadrants Positioned as Viewed from the Low-Pressure Side

LEAKAGE FLOW PERFORMANCE SUPERIMPOSED ON ROTATION , TEMPERATURE AND PRESSURE DIFFERENTIAL

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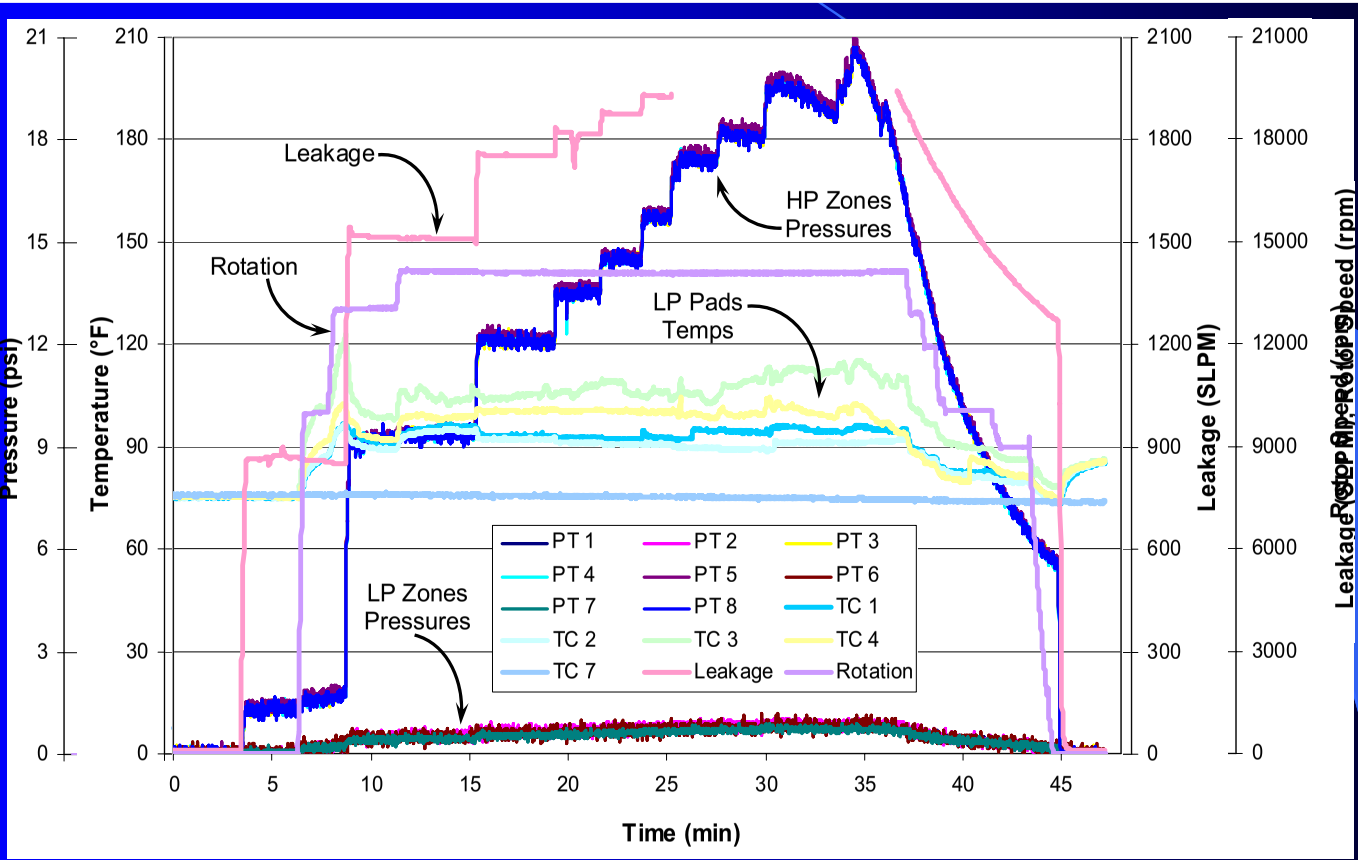

FLOW FACTOR vs. PRESSURE DIFFERENTIAL

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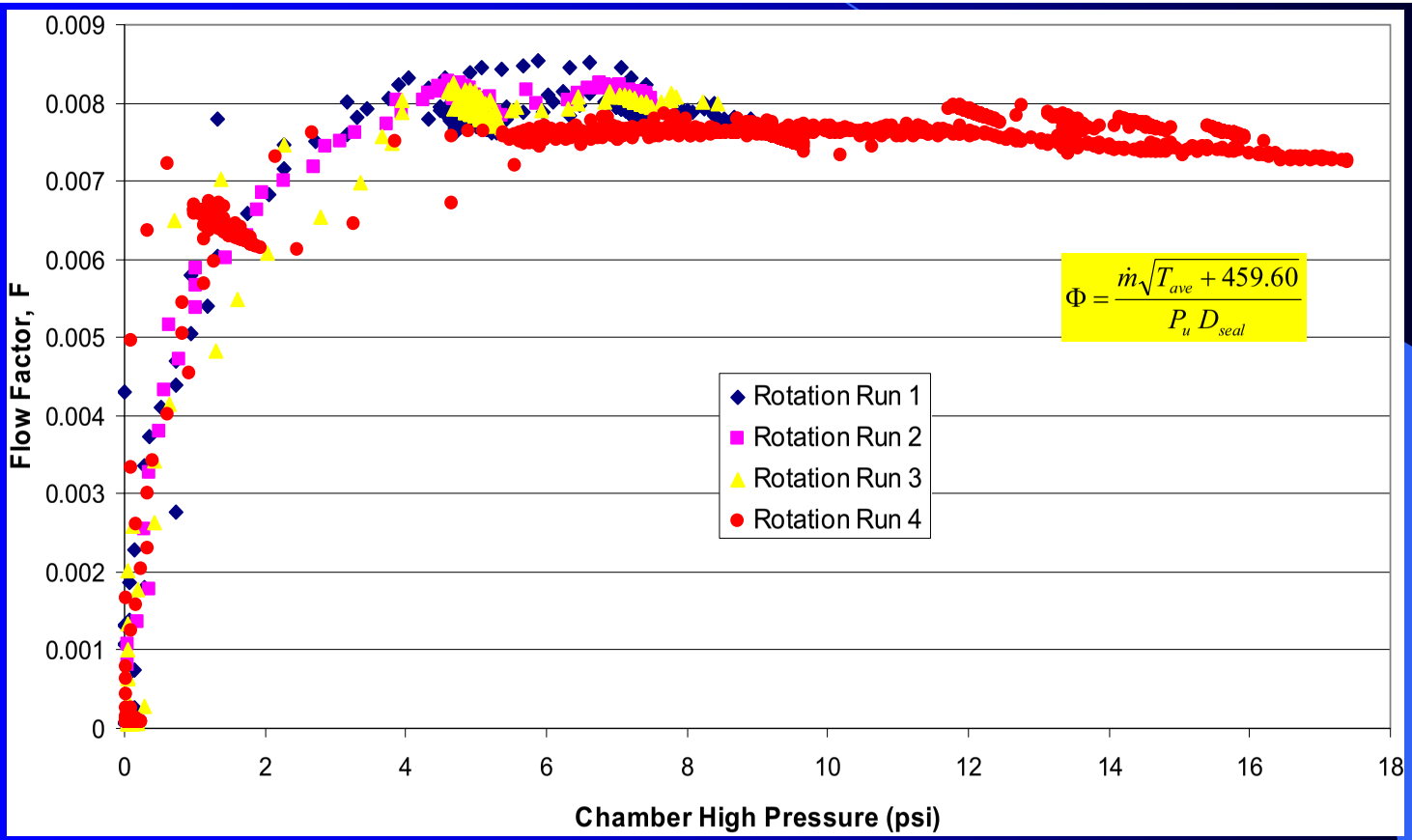

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