Advanced Natural Gas Reciprocating Engine: Parasitic Loss Control Through Surface Modification

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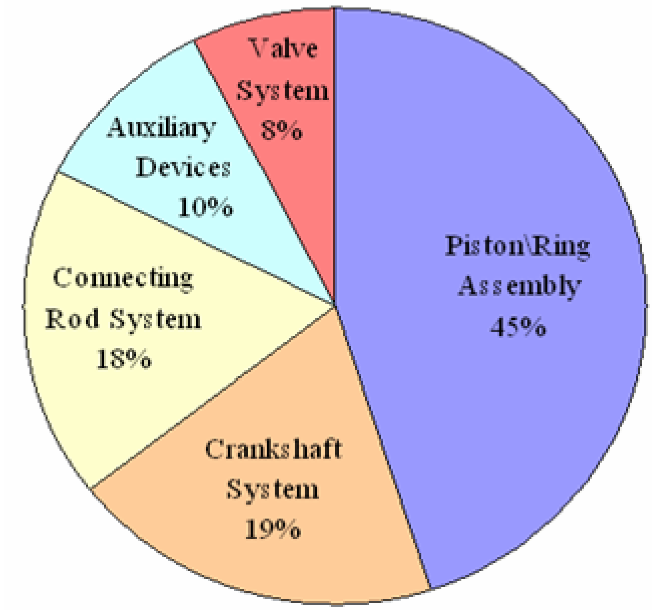
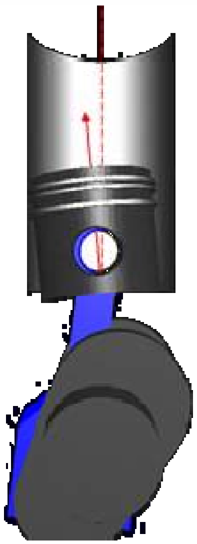
Presentation Outline

- Motivation & background
- Objectives
- Current Project Schedule
- Personnel
- Progress to Date
  - Experimental Studies
    - Piston Ring Reciprocating Liner Test Rig
    - PRCL Test Rig
  - Analytical Studies
    - Reynolds equation with cavitation
    - Stochastic and Semi-Deterministic modeling of piston rings with mixed lubrication
  - Development of Semi-Deterministic asperity contact model
  - Corroboration of experimental & analytical results
    - Friction reduction through surface modification
    - Experimental results
    - Full deterministic modeling of mixed lubrication – development
  - Results - Modified Surfaces
- Future Work
- Summary

Motivation & Background

- A significant portion of the engine frictional loss can be attributed to the piston/ring assembly
- A fundamental understanding of the lubrication at the Piston Ring Cylinder Liner (PRCL) interface is key to improving designs and in developing novel approaches to friction and/or wear reduction
- Friction is maximum near TDC & BDC where a combination of solid and lubricated contact (mixed lubrication) occurs
- Proper modeling of the mixed lubrication regime is critical to predicting frictional losses for rough and modified surfaces
- Previous computational models have shown significant gains in tribological performance when micro-dimples are introduced (Zhao & Sadeghi, 2001)





Overall Objectives

- The objectives of this study are to analytically and experimentally investigate the effects of surface patterning and features (e.g. dimples, negative skewness, etc.) on friction reduction, lubrication condition and improved efficiency of large bore natural gas engines

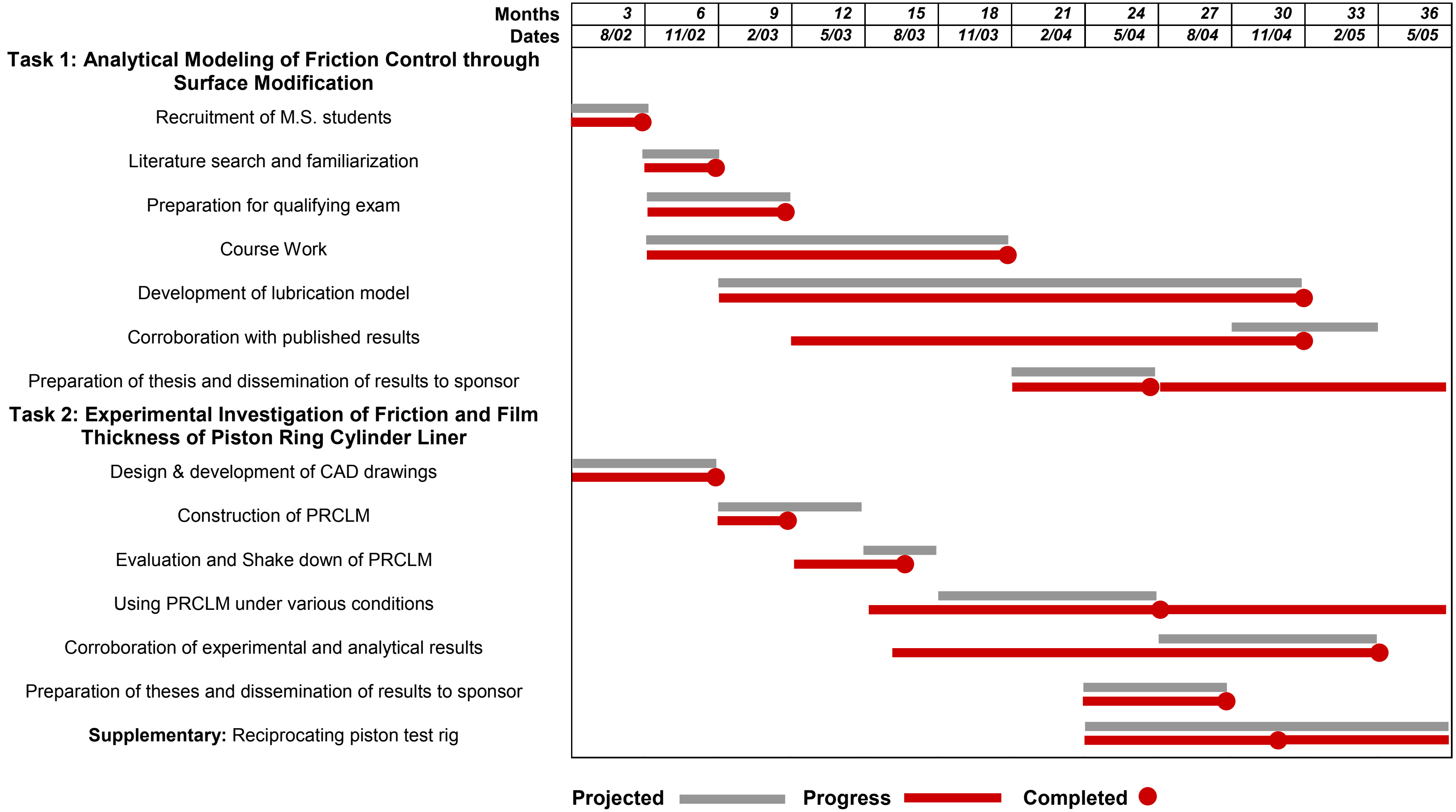
Experimental Study Objectives

- **Originally:** Design and develop a bench scale piston cylinder liner test rig operating under ambient condition
- **Supplementary:** Modify a single cylinder engine operating under ambient conditions
  - The test rigs will be used to measure friction between commercially available and surface pattern rings and cylinder liners operating under various conditions

Analytical Study Objectives

- Develop CFD models to simulate mixed, boundary and full film lubrication conditions (TBD & BDC) of the piston ring's motion in the cylinder liner. The model will then be extended to investigate surface patterning and feature effects on lubrication condition and friction reduction at the piston ring cylinder liner interface.
- **Corroborate analytical and experimental results.**

Current Project Schedule



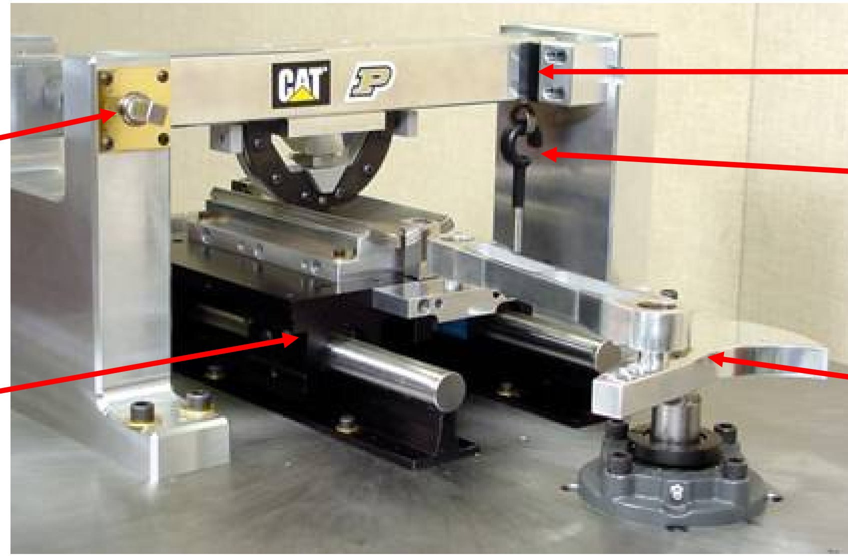
Personnel

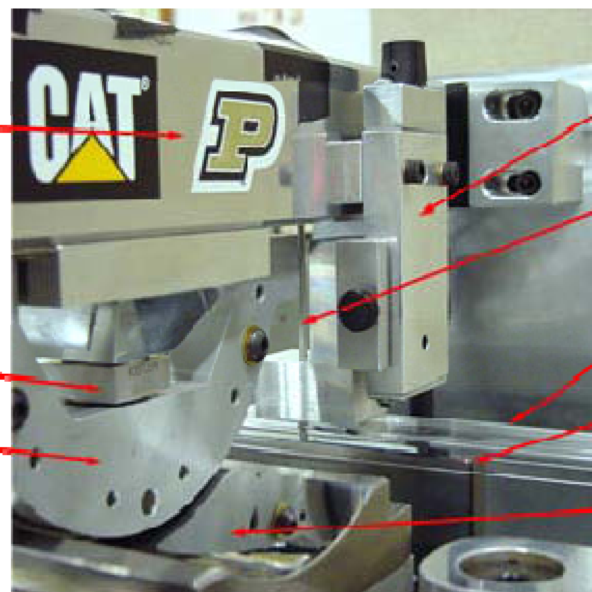
- Research Assistants
  - Nathan Bolander, PhD candidate
    - Analytical & Experimental Work
    - Expected Completion date 5/06
  - Brian Steenwyk, MS candidate
    - Experimental Work
    - Graduated in August 2004
      - Currently at Bridgestone
  - Chandrashekhar Varanasi, MS candidate
    - 1st class with Distinction at IIT Khargpour
    - Experimental Work
    - Will join the group in 8/05

Reciprocating Liner Test Rig

- Designed and developed (Brian Steenwyk, 2004)
- Controllable parameters:
  - Load and speed
    - ✓ Accommodate range of sample sizes:
      - ➢ 2” to 5-1/2” bore
      - ➢ 9” x 9” carriage size
      - ➢ Variable stroke: 1-1/2” to 6”
      - ➢ Variable speed direct DC drive
- Will not simulate all the details of an IC engine
- Can measure friction and film thickness between piston ring, commercially available liners and surface modified liners using a piezoelectric 3-axis force sensor and fiber optic sensors

Reciprocating Liner Test Rig

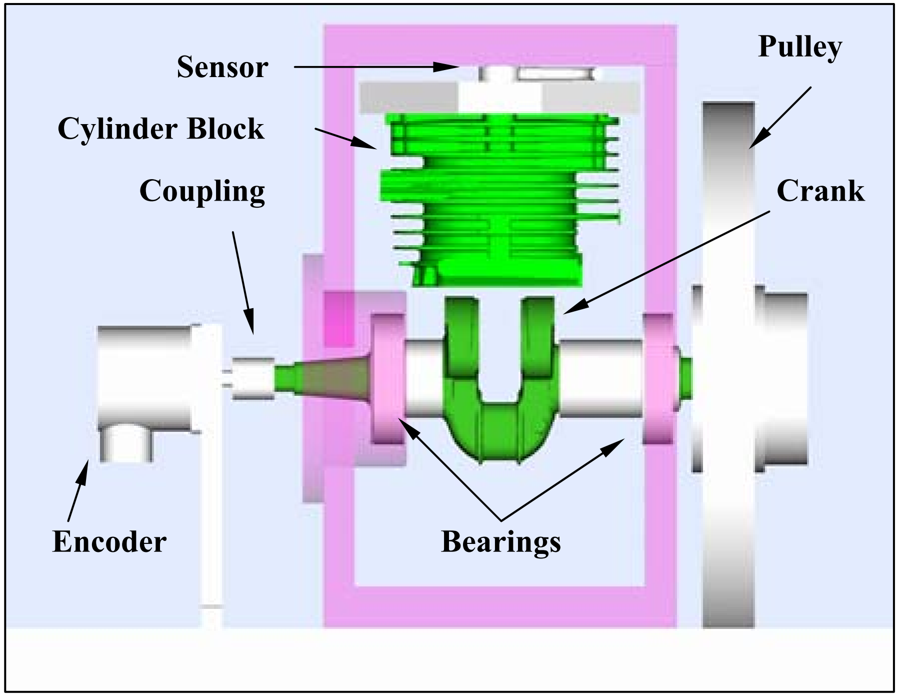


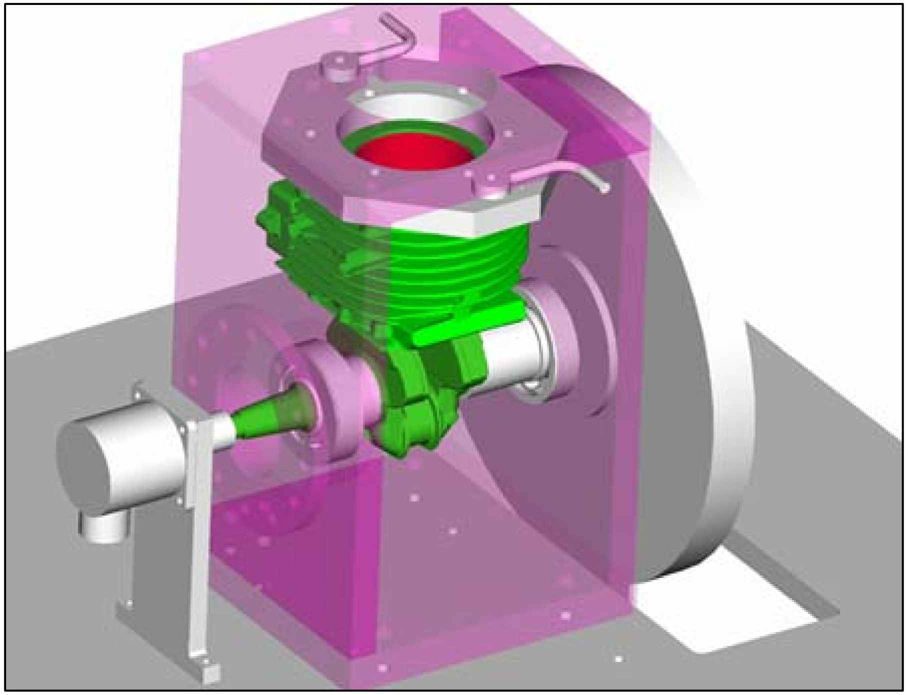


Reciprocating Piston Test Rig
(Goals, Variables & Attributes)

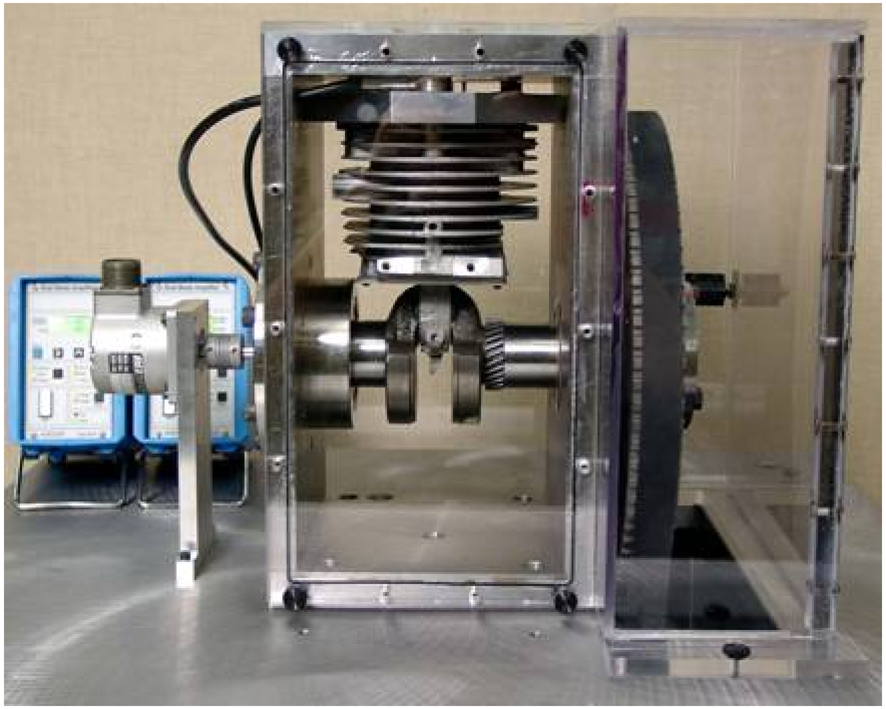
- Parts from a Tecumseh OHM90 single-cylinder, 4 stroke engine used in a floating liner arrangement
  - 3-1/8" bore
  - 2-7/32" stroke
  - Variable speed direct DC drive
- Controllable variables: speed, lubrication, surface finish
- Measure: friction, thrust load, crank angular position
- Closer to actual engine operation and dynamics

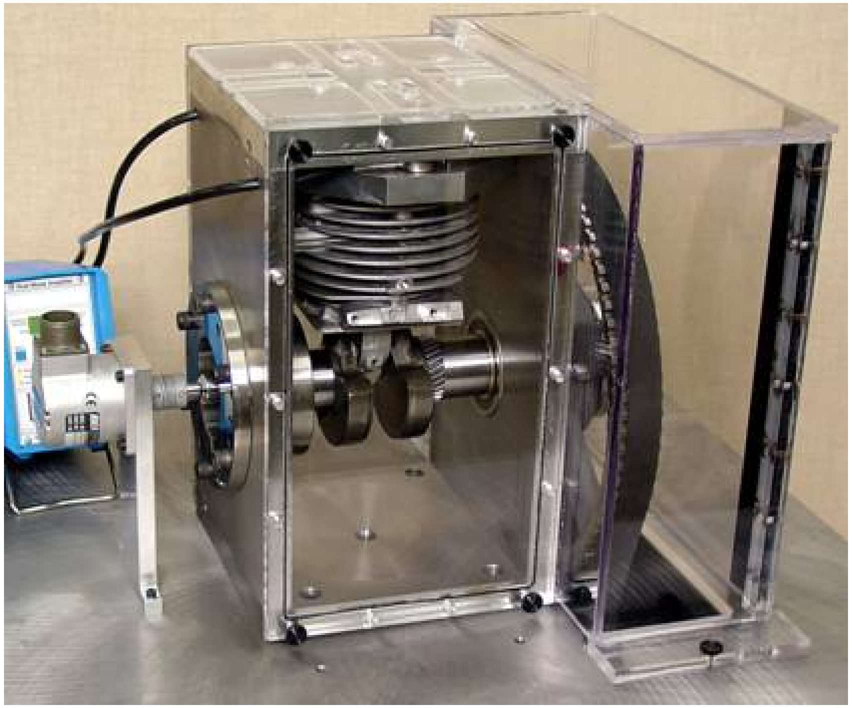
Reciprocating Piston Test Rig





Reciprocating Piston Test Rig





Reciprocating Piston Test Rig Results

- Friction behavior is very similar to Reciprocating Liner Test Rig
- Side load measured simultaneously

Modeling Summary

- Modeling approach
  - Stochastic
  - Semi-deterministic
    - Surface roughness
  - Fully deterministic

Numerical Modeling of Piston Ring Lubrication

- Numerical modeling is complimentary to experimental measurements
- Corroboration of numerical and experimental results are used to provide better understanding of conditions at the PRCL interface
- Some of the research work has been published
  - Bolander, N.W., Steenwyk, B.D., Sadeghi, F., Gerber, G.R., “Lubrication regime transitions at the piston ring-cylinder liner interface”, Proc. Inst. Mech. Engrs, Part J: J. Engineering Tribology, **219,** (In Print)
  - Bolander, N.W., Steenwyk, B.D., Kumar, A., Sadeghi, F., “Film Thickness and Friction Measurement of Piston Ring Cylinder Liner Contact with Corresponding Modeling including Mixed Lubrication”, ICED Fall Technical Conference Proceedings, ASME Paper ICEF2004-903

Piston Ring Lubrication
(Background)

- The choice of cavitation boundary condition can have a major influence on the predicted load support capacity
  - Dowson et al. (1978) – Half Sommerfeld
  - Jeng (1992) – Reynolds (Swift-Stieber)
  - Sawicki and Yu (2000) – JFO cavitation
- Asperity contact plays a major role in the frictional loss near top-dead-center and bottom-dead-center due to decreased hydrodynamic action. This has typically been handled using a statistical model for asperity contact pressure (Greenwood & Tripp)
  - Rohde et al. (1980), Hu et al. (1994), Akalin and Newaz (2001)
- Elastic deformation of the ring must be considered near TDC
  - Dowson et al. (1983), Yang & Keith (1995)

Governing Equations

- Time dependent Reynolds equation for isothermal condition including cavitation:

$$\frac{\partial}{\partial X}\left(H^3\frac{\partial(F\phi)}{\partial X}\right)=\gamma\frac{\partial}{\partial X}\left[\left(1+(1-F)\phi\right)H\right]+\sigma\frac{\partial}{\partial T}\left[\left(1+(1-F)\phi\right)H\right]$$

- Function ϕ

$$\frac{p-p_c}{p_a-p_c}=F\phi \quad \text{in the full film region}$$

$$\frac{\rho}{\rho_c}=1+(1-F)\phi \quad \text{in the cavitation zone}$$

cavitation index

$$F(x)=1 \quad \text{for} \quad \phi\geq 0$$

$$F(x)=0 \quad \text{for} \quad \phi<0$$

- Note that ϕ is a dimensionless pressure in the full film region and that $(1+\phi)$ is the partial film content in the cavitation zone

Governing Equations

- Film Thickness equation:

$$H_l(X,Y,\theta) = H_c(\theta) + \frac{X^2}{2} + \frac{\kappa^2 Y^2}{2r} + \delta_{1,2}(X,Y,\theta) + \frac{2c}{\pi^2}\iint_\Omega \frac{P_l(X',Y',\theta')\,dX'dY'}{\sqrt{(X-X')^2 + (Y-Y')^2}}$$

- Viscosity & density variation with pressure:

$$\bar{\eta}(P) = e^{\left[\ln(\eta_0)+9.67\right]\left[\left(1+p_h P/1.98\times10^8\right)^z - 1\right]} \qquad \bar{\rho}(P) = \frac{0.59\times10^9 + 1.34\,p_h P}{0.59\times10^9 + p_h P}$$

Governing Equations

- The friction force is calculated by summing the contributions from both the fluid shear and the solid contact

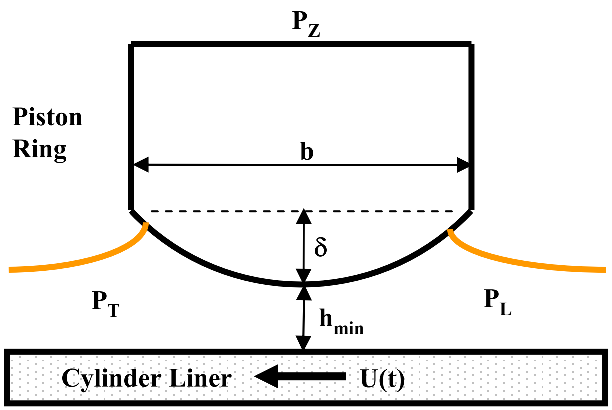
$$F_{f,fluid} = \iint_{\Omega} \left(\tau_{zx}\right)_{z=0} dA \qquad F_{f,solid} = \mu_{solid} \iint_{\Omega} P_s dA$$

- The load balance is calculated by summing the contributions from both the fluid pressure and the asperities in contact

$$F_l = \iint_{\Omega_l} P_l\left(X,Y,\theta\right) dXdY$$

$$F_s = \iint_{\Omega_s} P_s\left(X,Y,\theta\right) dXdY$$

$$F_l + F_s = \frac{2\pi}{3}$$



Solution Technique

- Finite Difference Method for the Reynolds equations
- Fast Fourier Transform (FFT) for the elasticity equation
- Solid Contact:
  - Minimize Complementary Energy
  - FFT

$$\min f\left(P_s\right) = \frac{1}{2}\int\int_{\Omega_s} P_s H_s dXdY + \int\int_{\Omega_s} P_s H_s dXdY$$

$$\Downarrow$$

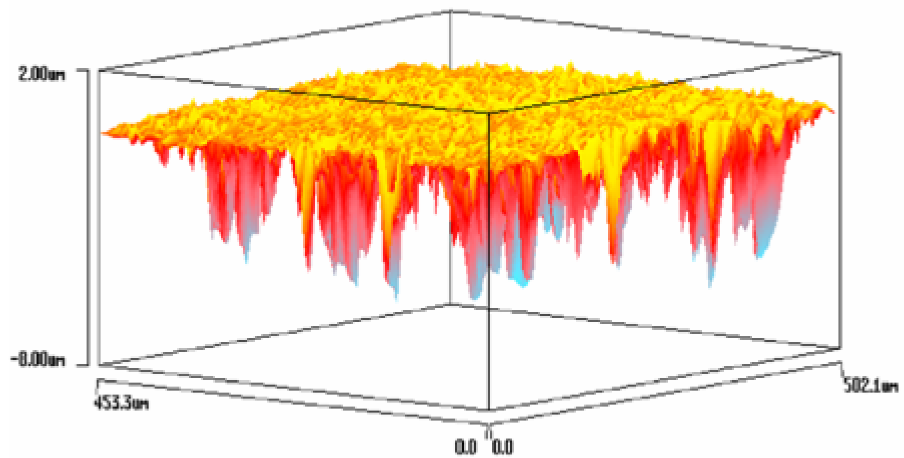
$$P_s^{new} = P_s^{old} - \omega_s\left(H_s^{old} + H_l^{old}\right)$$

Semi-Deterministic Modeling of Asperity Contact Pressures in Mixed Lubrication

- Surfaces are generated with statistics matching the experimentally measured values (Rq, Sk, Ku)
- Asperity contact pressure/deflection relationships are calculated for a number of non-Gaussian surfaces
- Asperity pressure map is used in place of the stochastic model

Generating Rough Surfaces

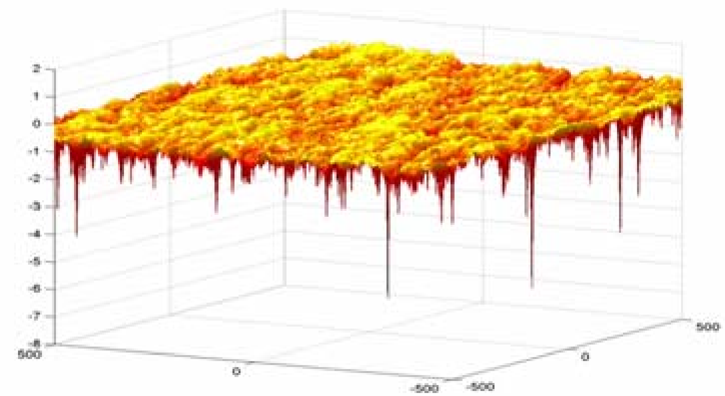
Measured



- OEM surfaces are measured using optical profilometer
- RMS roughness, skewness, kurtosis, and autocorrelation length are recorded
- Random surface is numerically generated to match the measured surface characteristics

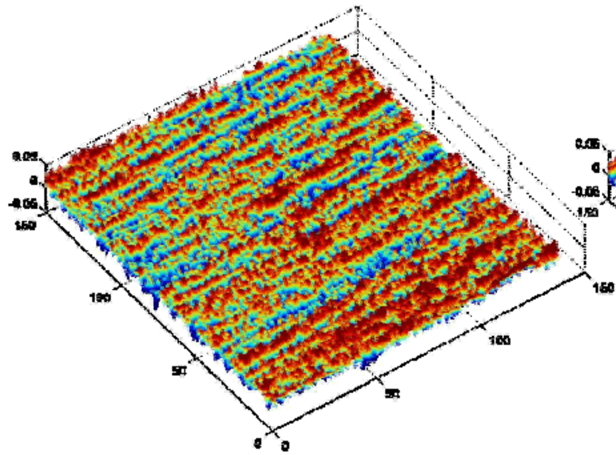
- Rq = 0.26 μm
- Sk = -3.56
- Ku = 44.7

Generated

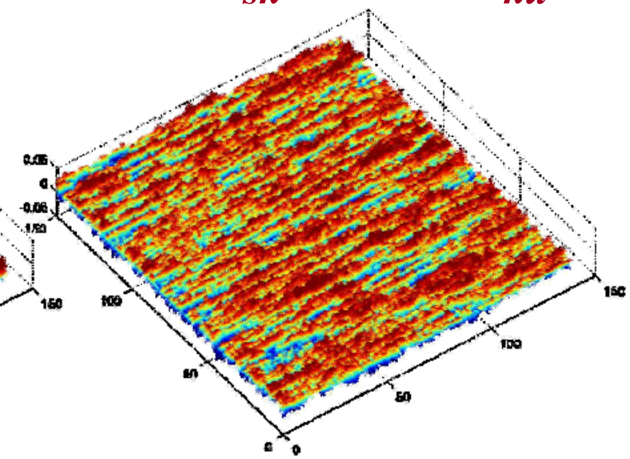


Generated Rough Surfaces

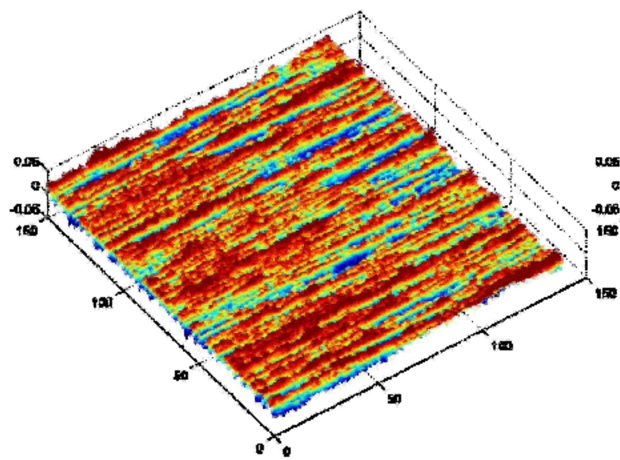
(with a specific lay, R_q=9.4 nm, R_{sk}=0.08, R_{ku}=3.0)



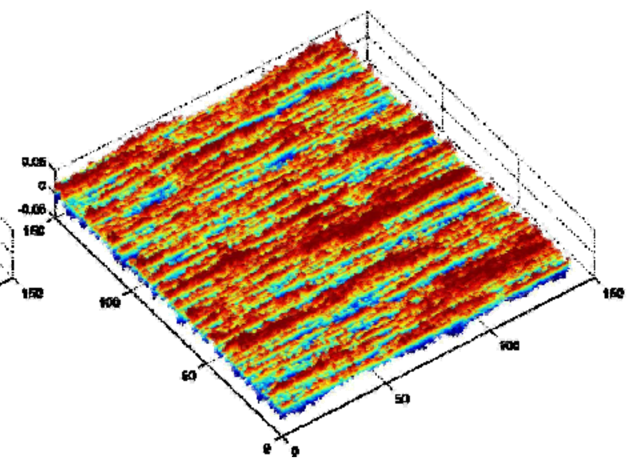
a - Measured Surface



b - Generated Surface #1



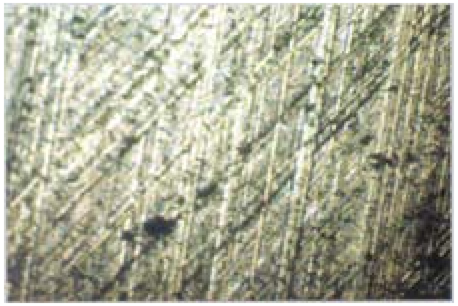
c – Generated Surface #2

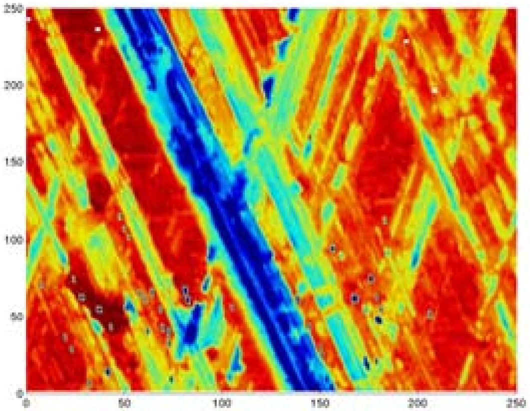


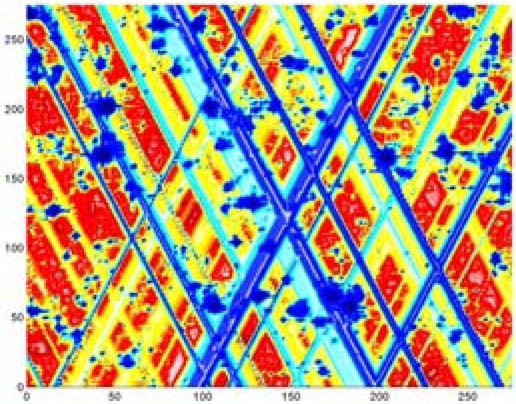
d – Generated Surface #3

OEM & Generated Rough Surface

(with cross hatching)



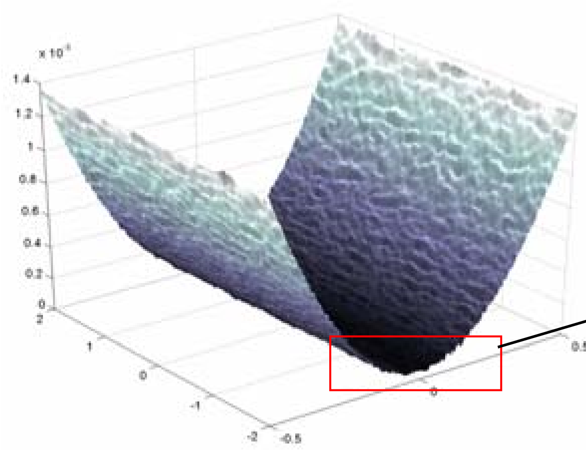


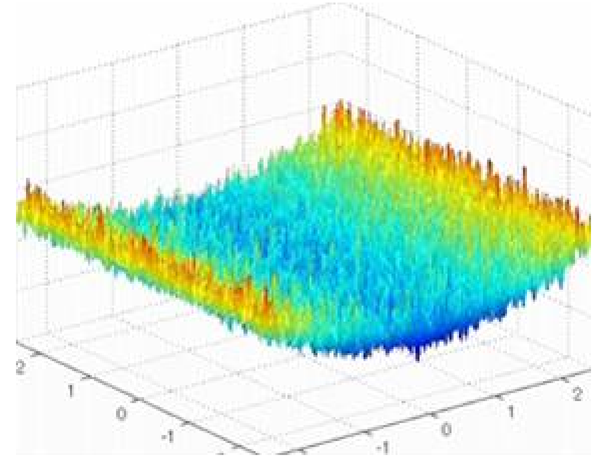


Measured

Simulated

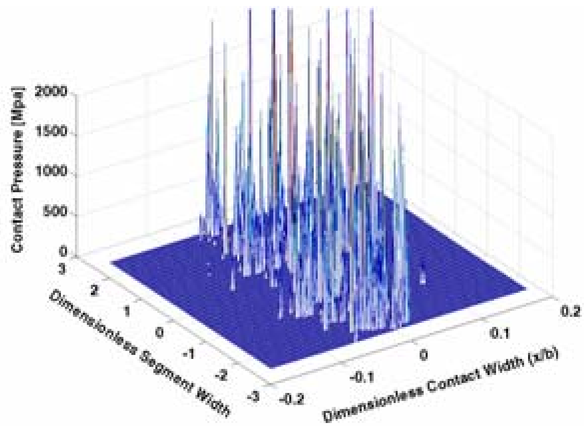
Semi-deterministic Asperity Contact Model



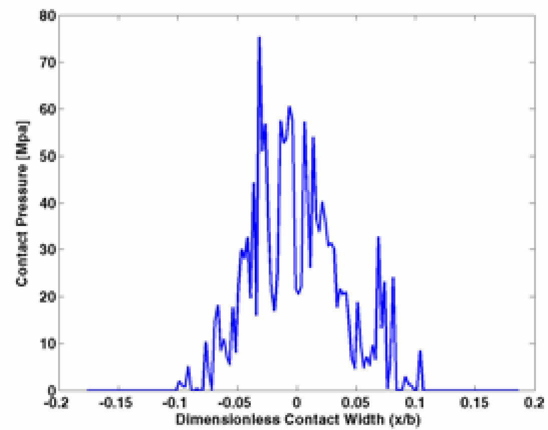


A given surface roughness is superimposed upon the parabolic ring profile

Asperity contact pressure is explicitly calculated over the limited contact region using a dry solid contact solver



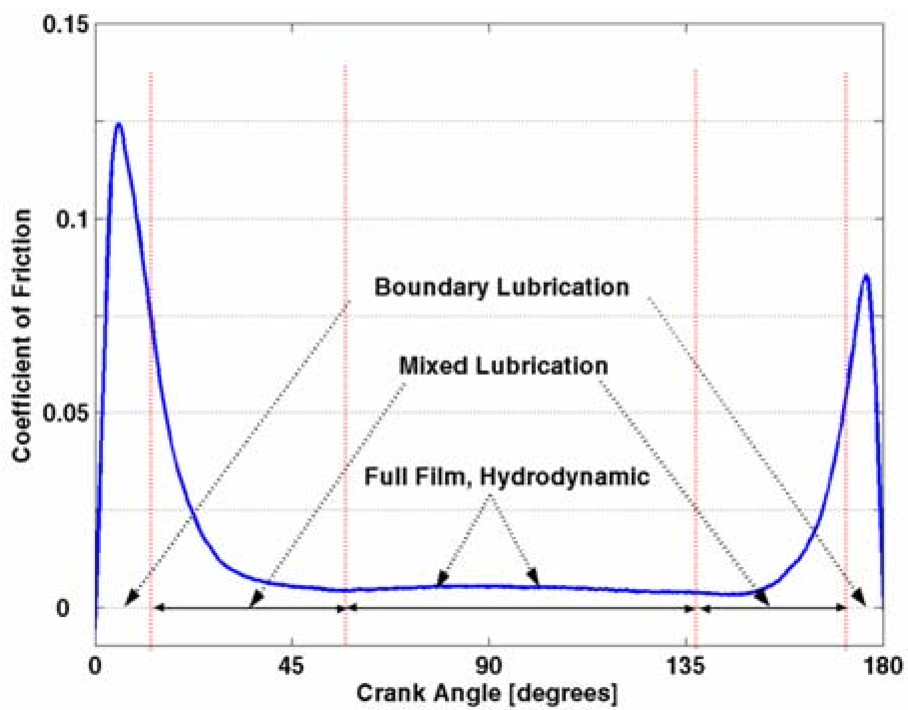
Two-dimensional contact pressure for a single segment

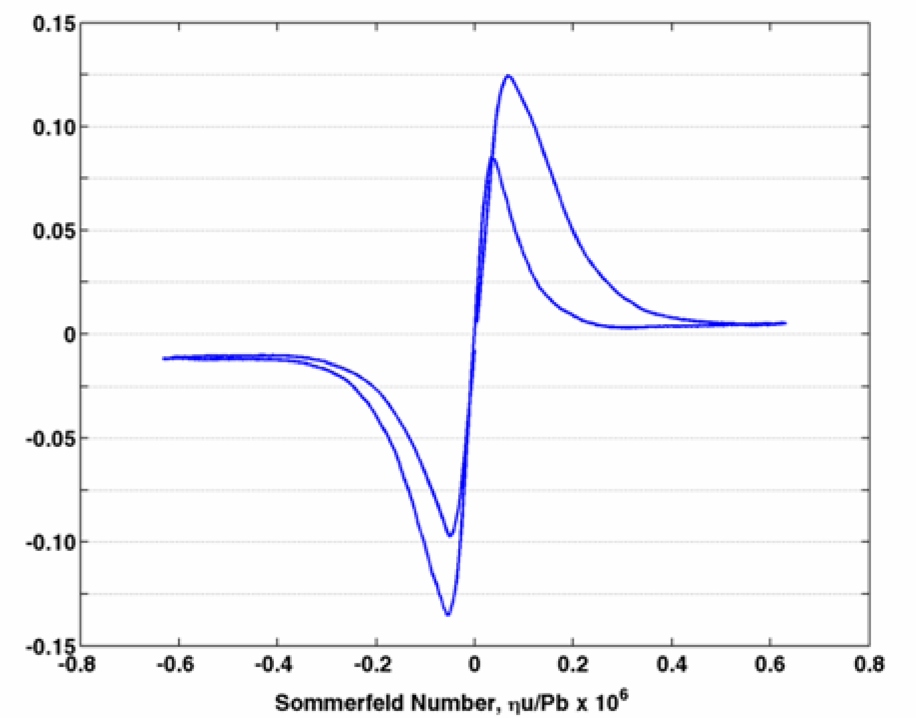


One-dimensional contact pressure averaged over the segment width

Typical Experimental Results

(Unmodified ring, 30 rpm, 3 kgf load)



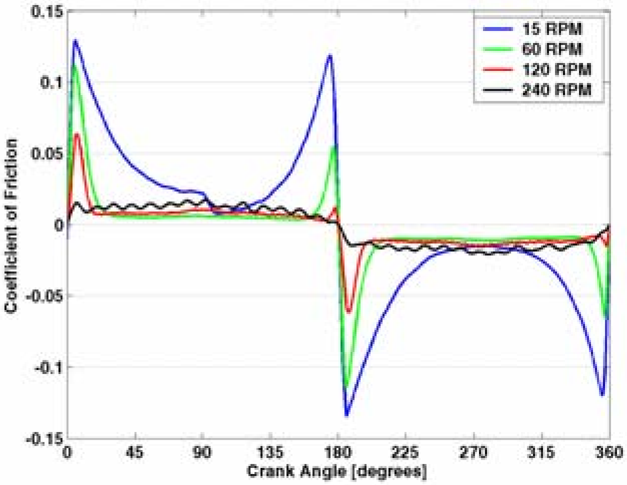


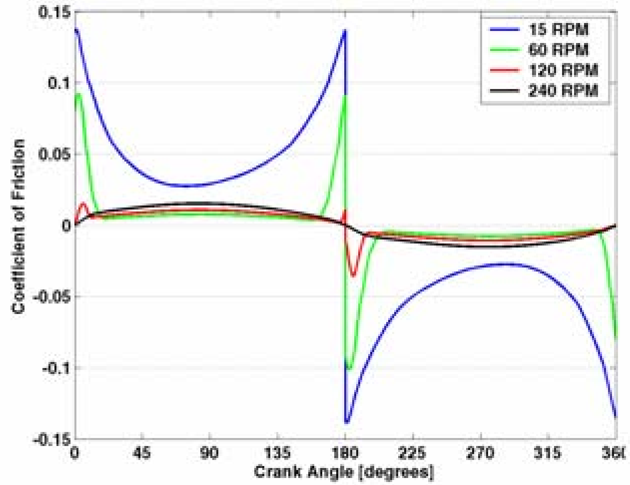
Friction vs. Crank Angle

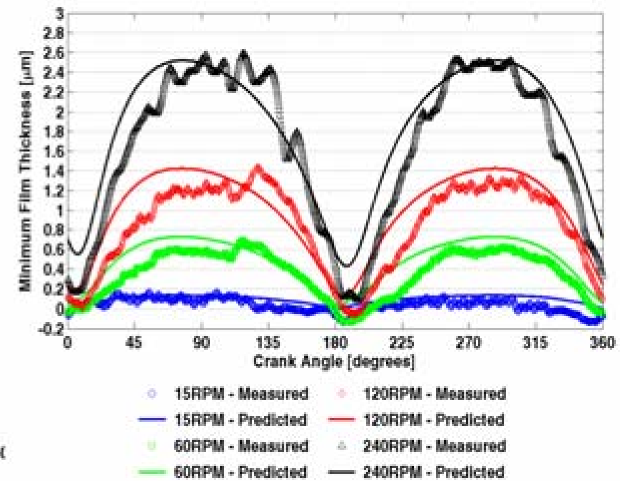
Stribeck-Type Diagram

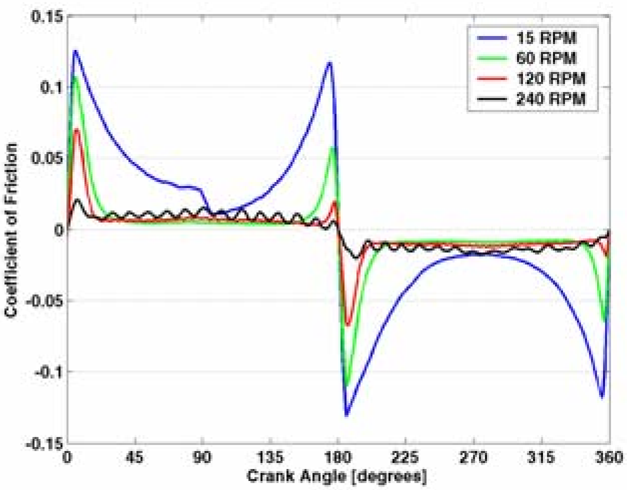
Experimental Results

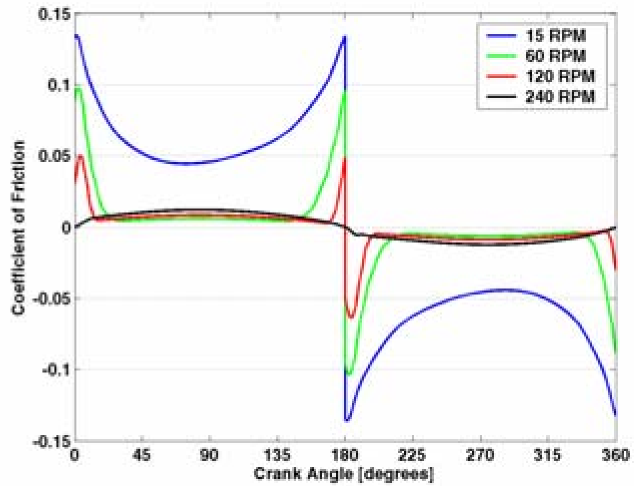
(Effect of Speed, Loads = 6 & 9 kg)

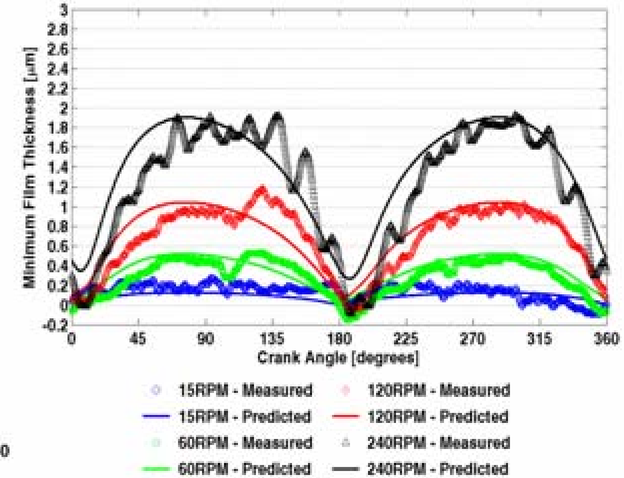












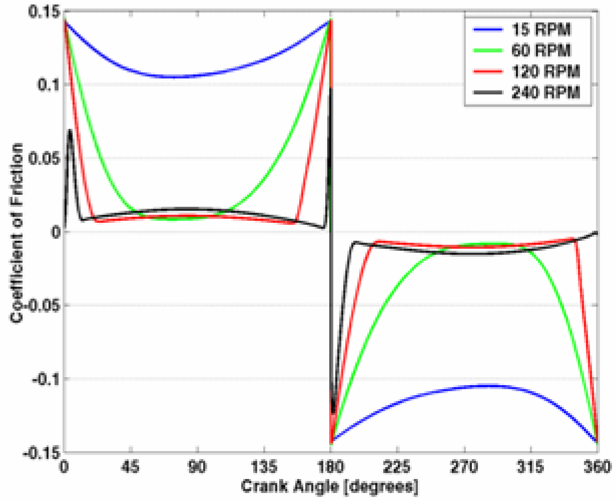
Measured Friction

Predicted Friction

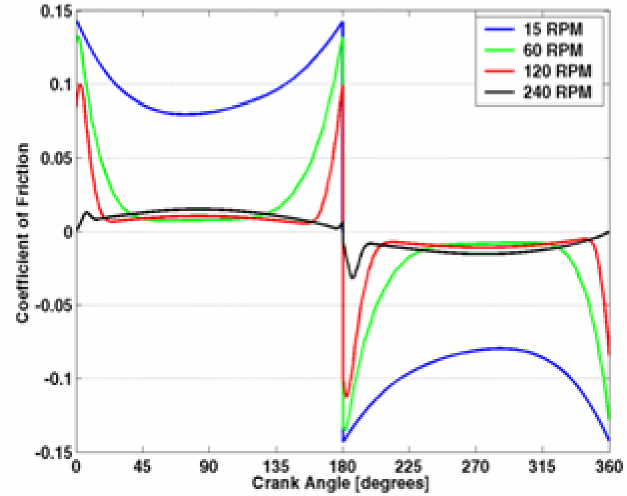
Measured & Predicted Minimum Film Thickness

Effect of Non-Gaussian Surfaces

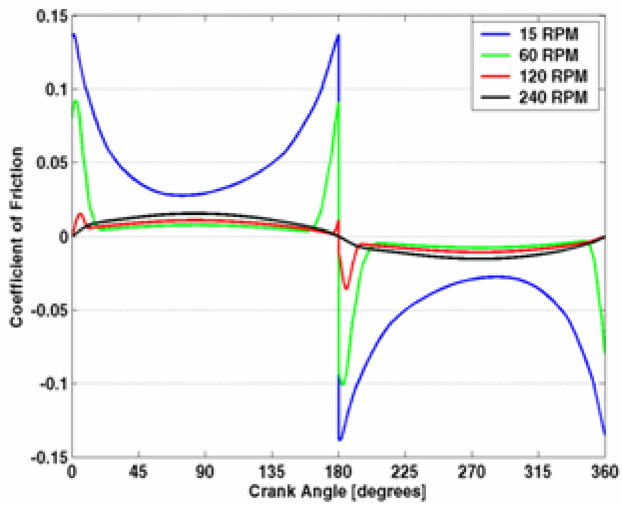
- **Use of Gaussian surface distribution leads to over-prediction of frictional losses at the ends of stroke in both the stochastic and semideterministic models**
- **Roughness amplitude alone is inadequate to describe the friction induced by asperity contact**
- **Skewness and kurtosis characteristics of the surface must also be considered**



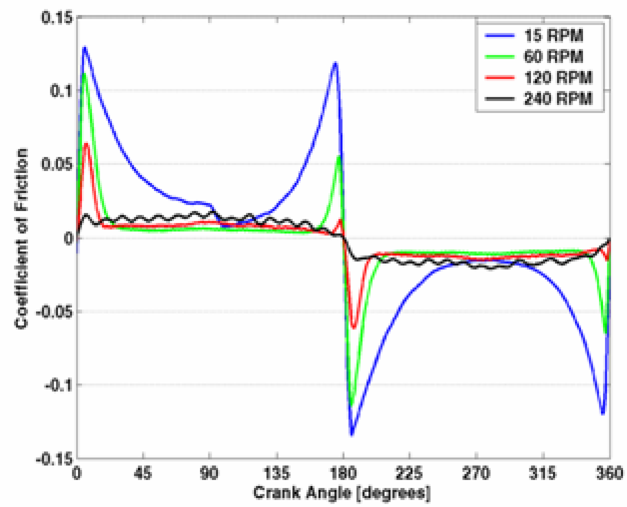
a) Greenwood and Tripp
(Rq = 0.26 um)



b) Semideterministic, Gaussian surfaces
(Rq = 0.26 um, Sk = 0.0, Ku = 3.0)



c) Semideterministic, non-Gaussian surfaces
(Rq = 0.26 um, Sk = -3.6, Ku = 44)



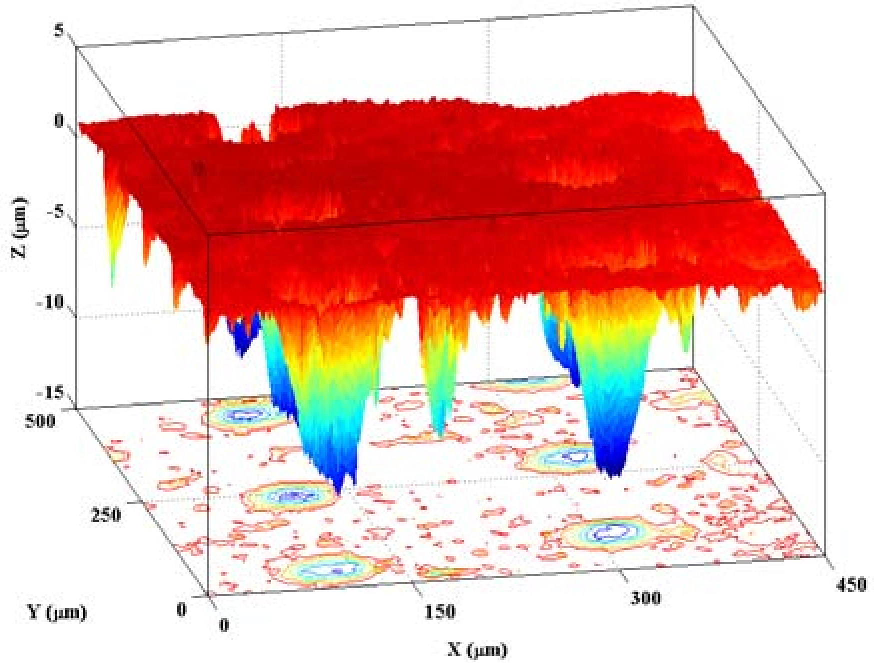
d) Measured, non-Gaussian surfaces
(Rq = 0.26 um, Sk = -3.6, Ku = 44)

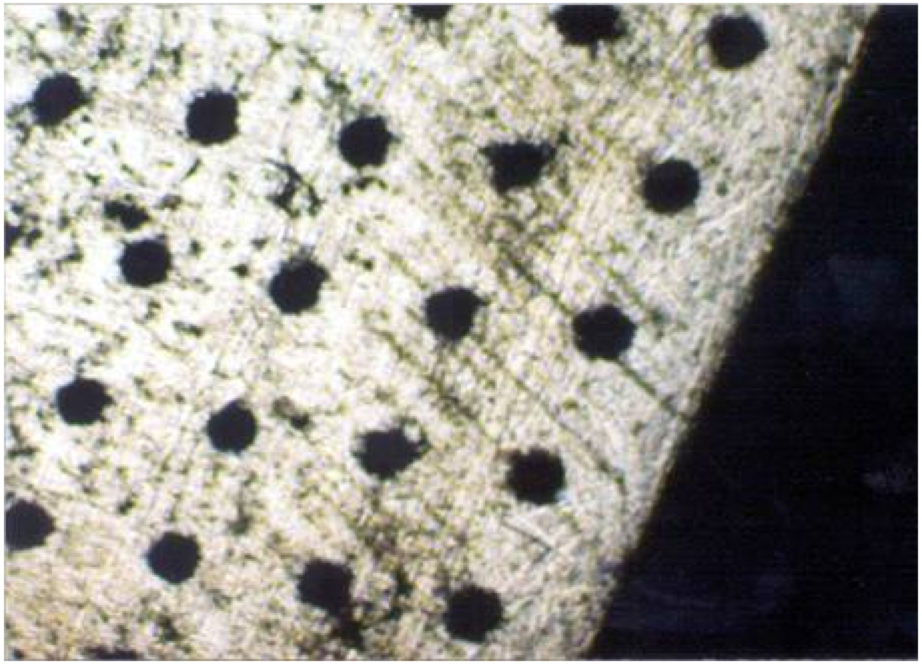
Friction Reduction through Surface Modification

- Experimental test rigs have been developed that provide repeatable data for friction and film thickness
- Numerical models show good correlation with experiments for unmodified surfaces
- Goal is to reduce parasitic loss
- Investigate modification of the contacting surfaces as a means of reducing friction
  - Experimental measurements
  - Numerical modeling

Modified Piston Ring Surface

Laser Machined Dimples

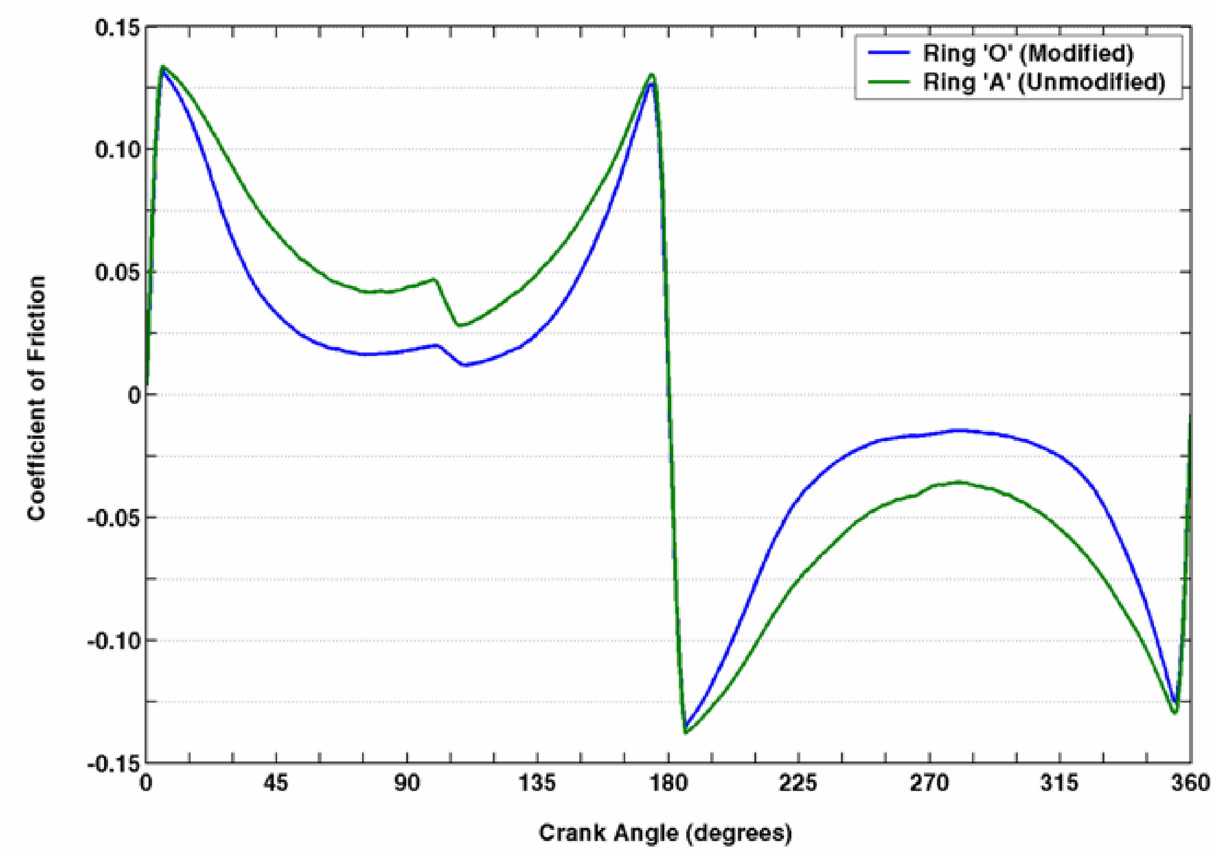




Range of dimple dimensions

Depth	3 – 11 μm
Width	75 – 123 μm

Modified Ring on Polished Liner



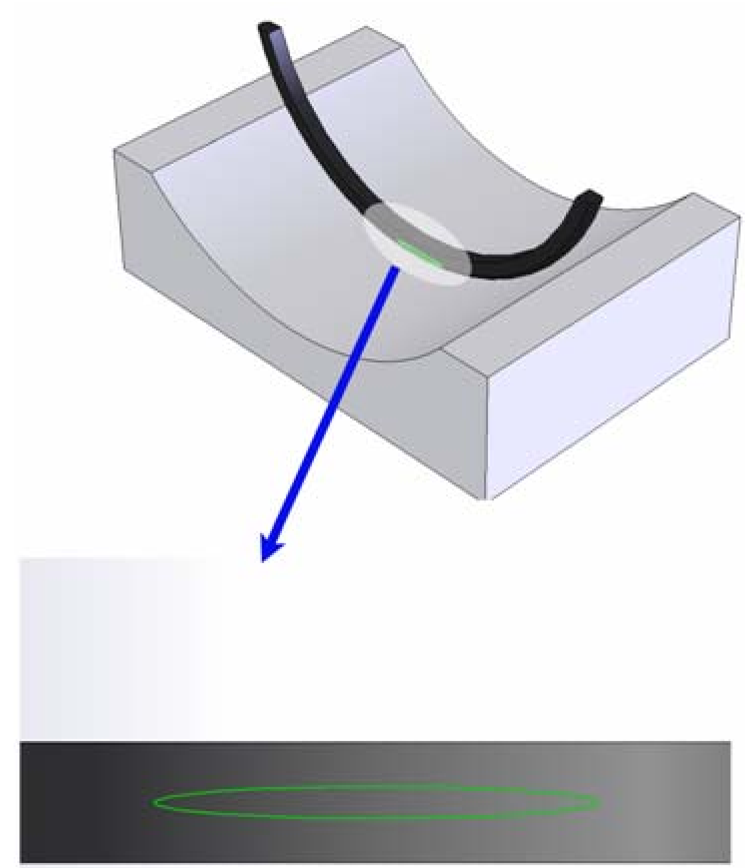
- Speed is slow enough for entire stroke to be mixed-lubrication
- NOTE: Mixed-lubrication regime friction is reduced

Analytical Background

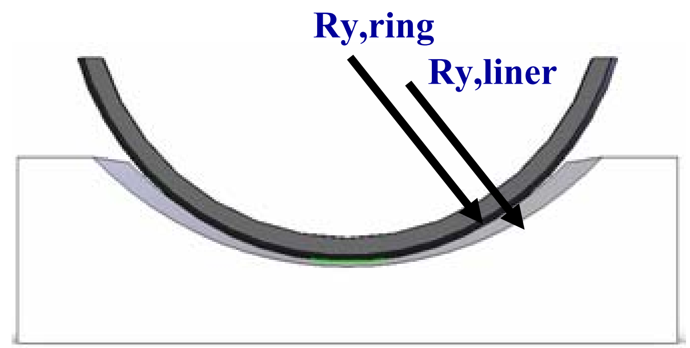
Deterministic Modeling of Mixed Lubrication

- Advances in computing power have made the deterministic modeling of mixed lubrication possible
  - Jiang et al. (1999), Hu & Zhu (2000), Zhao & Sadeghi (2000)
- The effect of surface modification can be computed directly
- Resolving the contact into full film and solid/solid regions allows for more accurate prediction of friction
- Direct modeling allows us to examine the fundamental mechanisms behind the benefits that result from surface with specific property and pattern

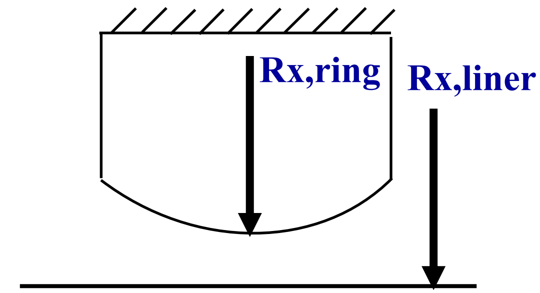
PRRL Contact Geometry



- Elliptical Contact

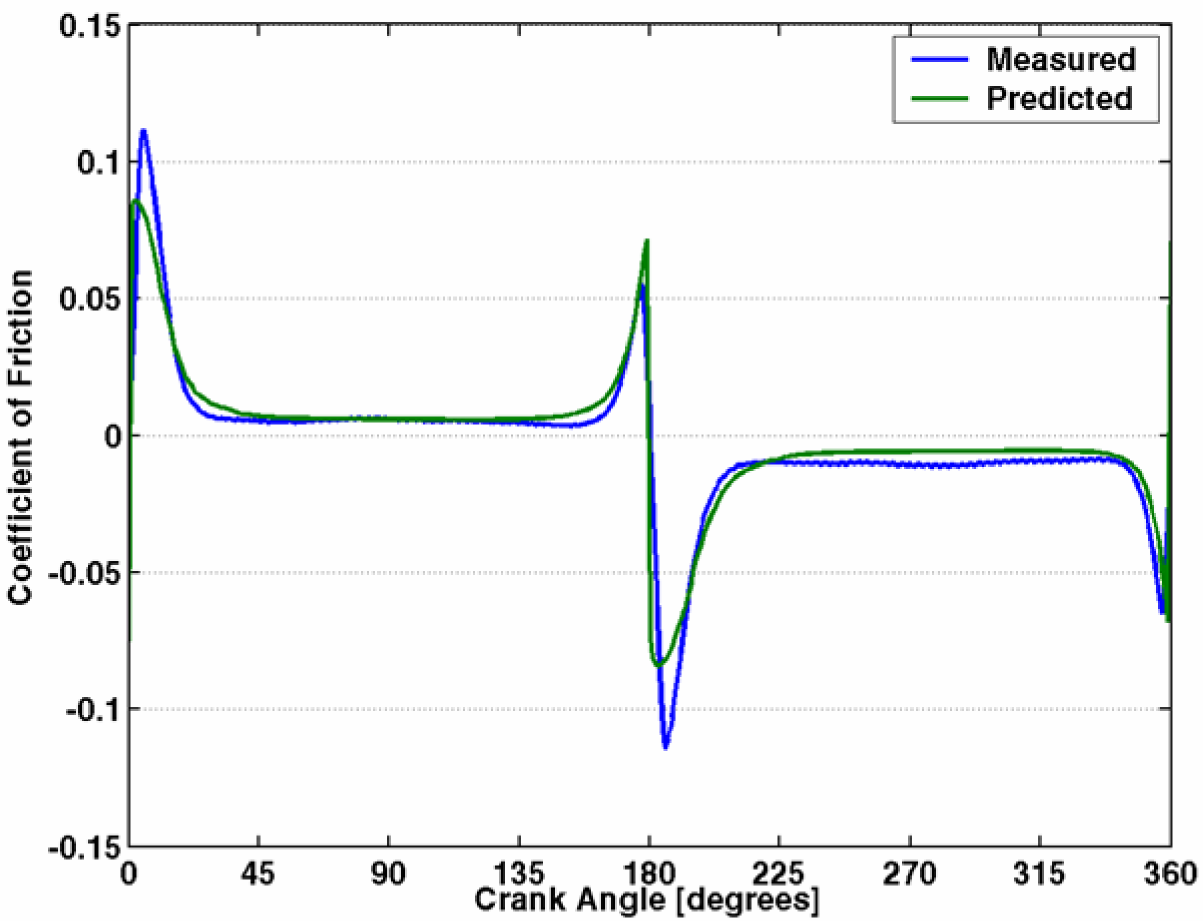


Front View
Ry,ring = 65.4 mm
Ry,liner = 68.6 mm
Ry,eq = 1.42 m



Side View
Rx,ring = 83.0 mm
Rx,liner = ∞
Rx,eq = 83.0 mm

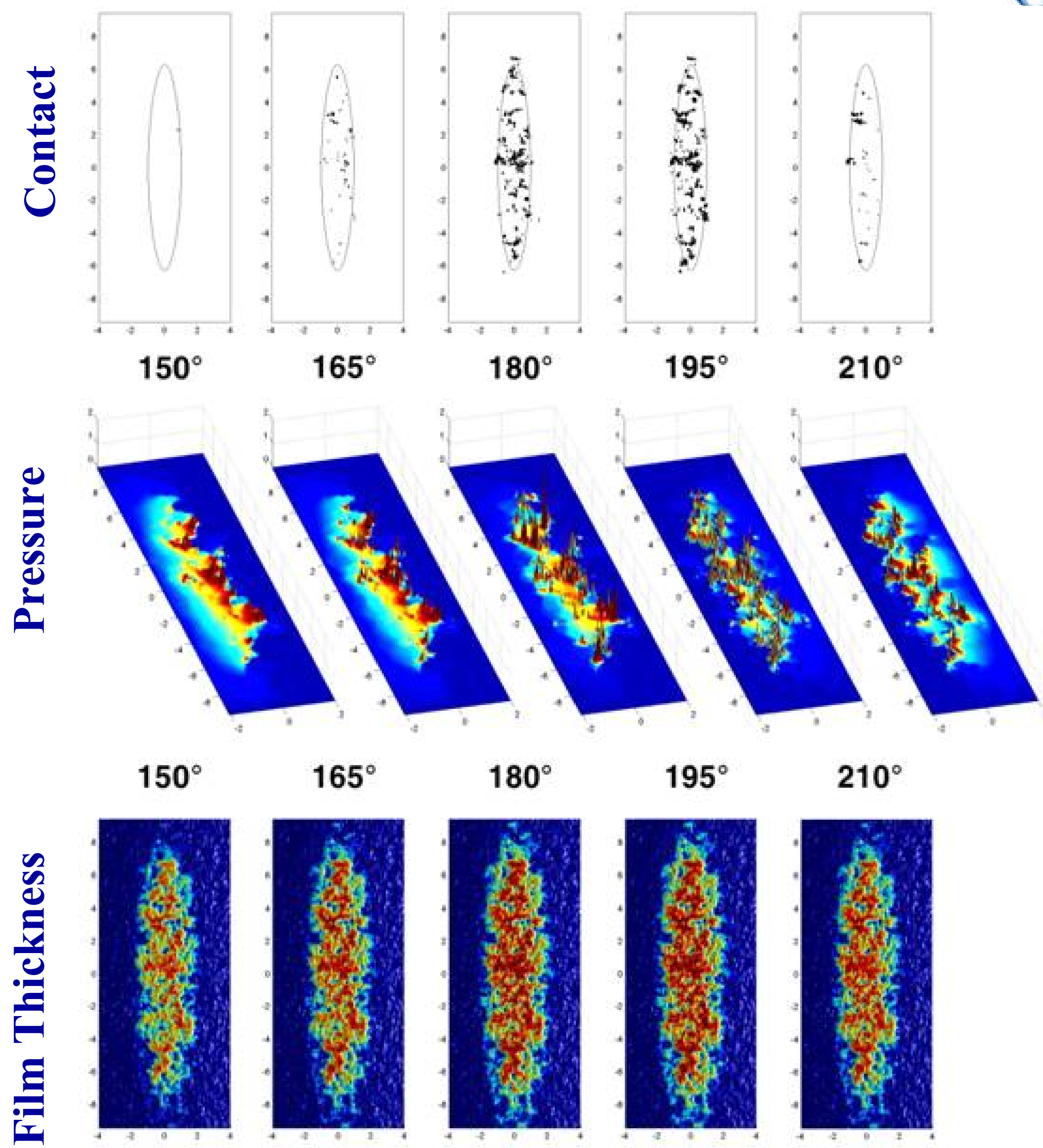
Correlation of Experimental and Analytical Results



Ring 'A': 6 kgf, 60 rpm, R_q = 0.26 µm, Sk = -3.04, Ku = 44.3

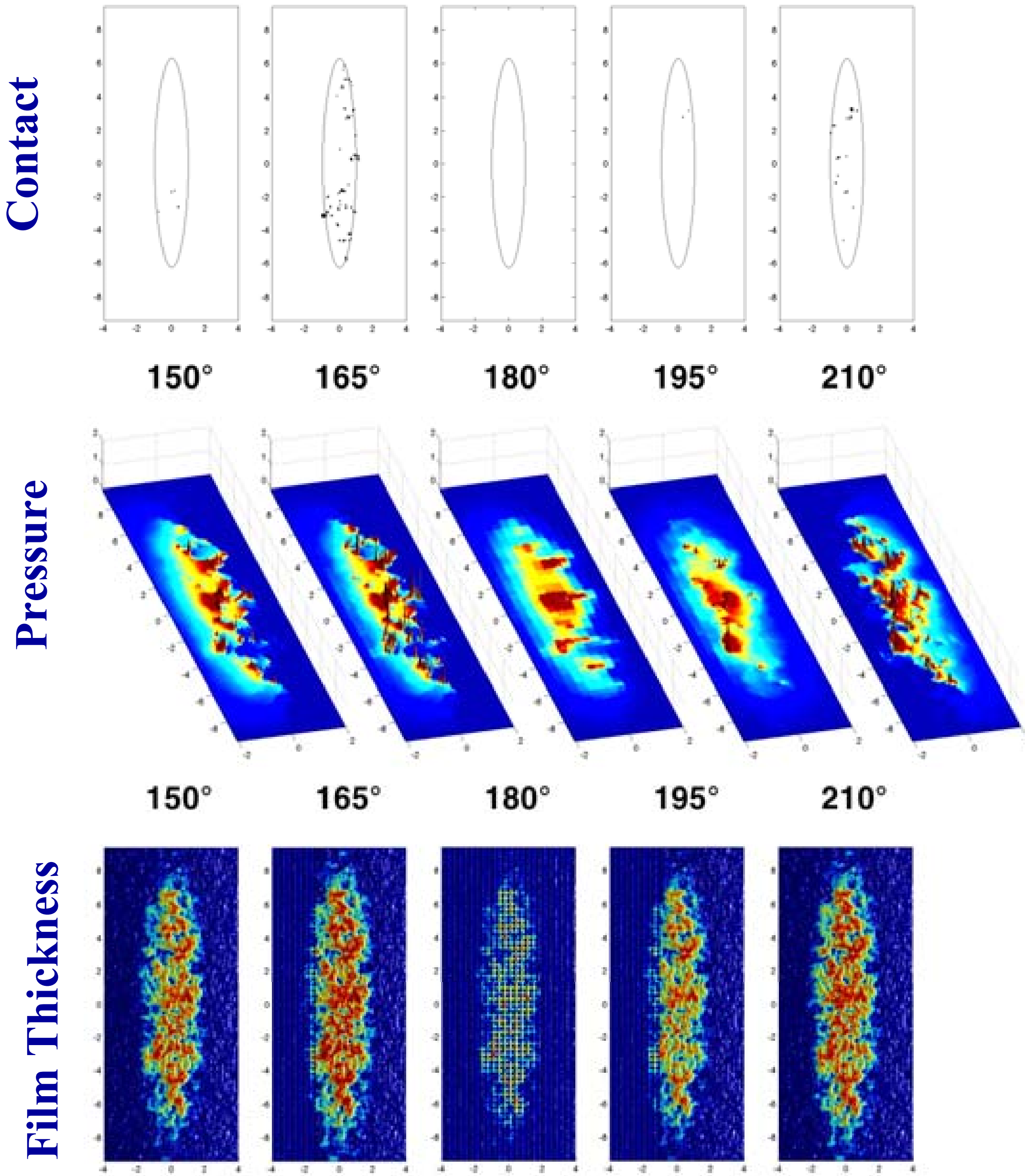
Unmodified Ring near BDC

- 6 kgf load, 60 rpm
- Rq = 0.26 mm
- Sk = -3.56
- Ku = 44.7

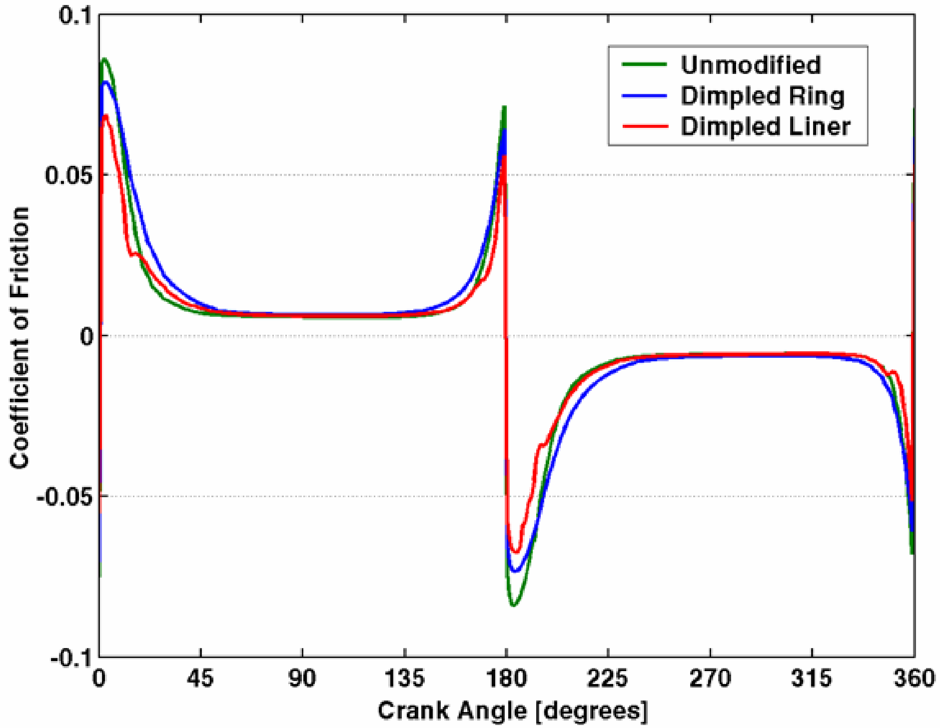


Modified Ring near BDC

- 6 kgf load, 60 rpm
- 50% area coverage
- 50 μm wide, 5 μm deep
- Asperity contact has been
- greatly reduced.
- Movie – Unmodified
- Movie – Modified Liner, 50%



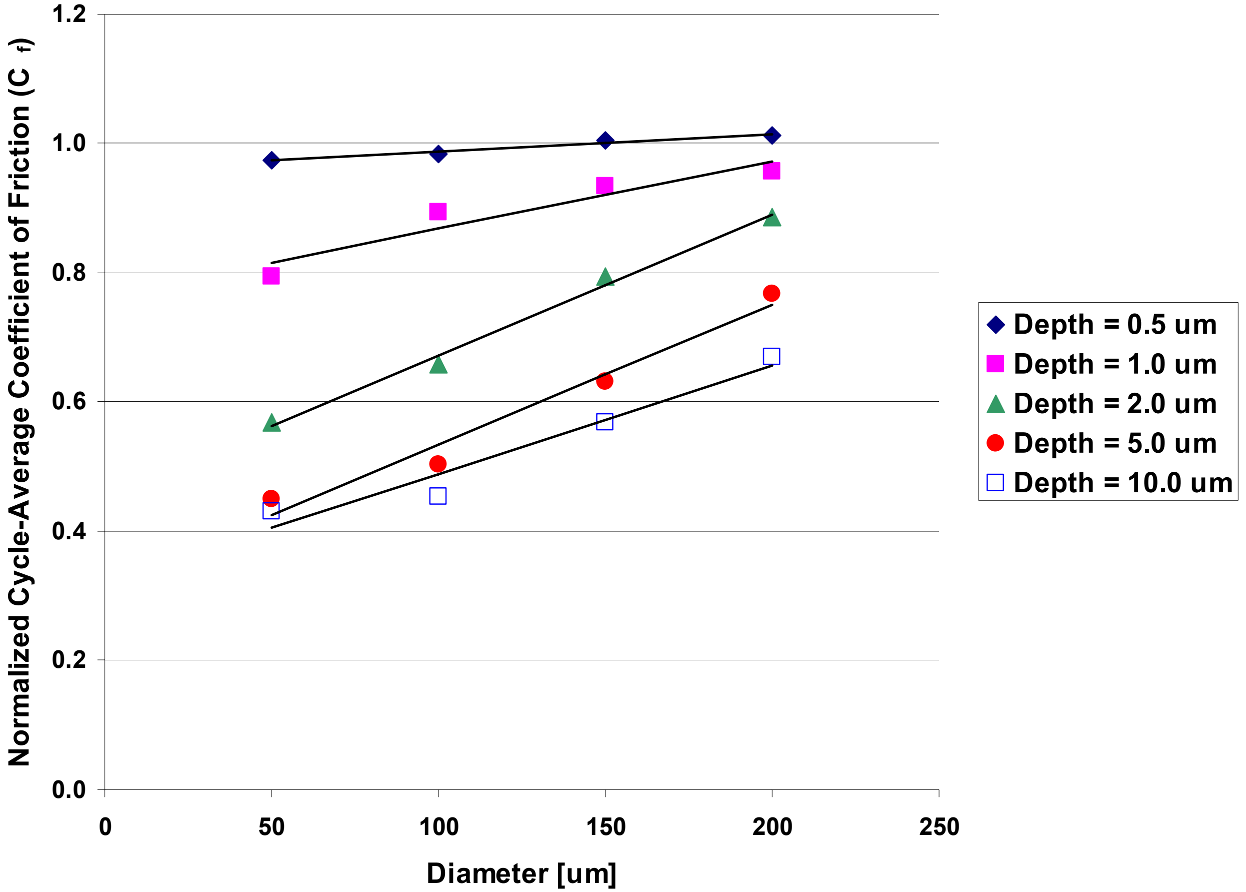
Frictional Loss for Modified Ring/Liner



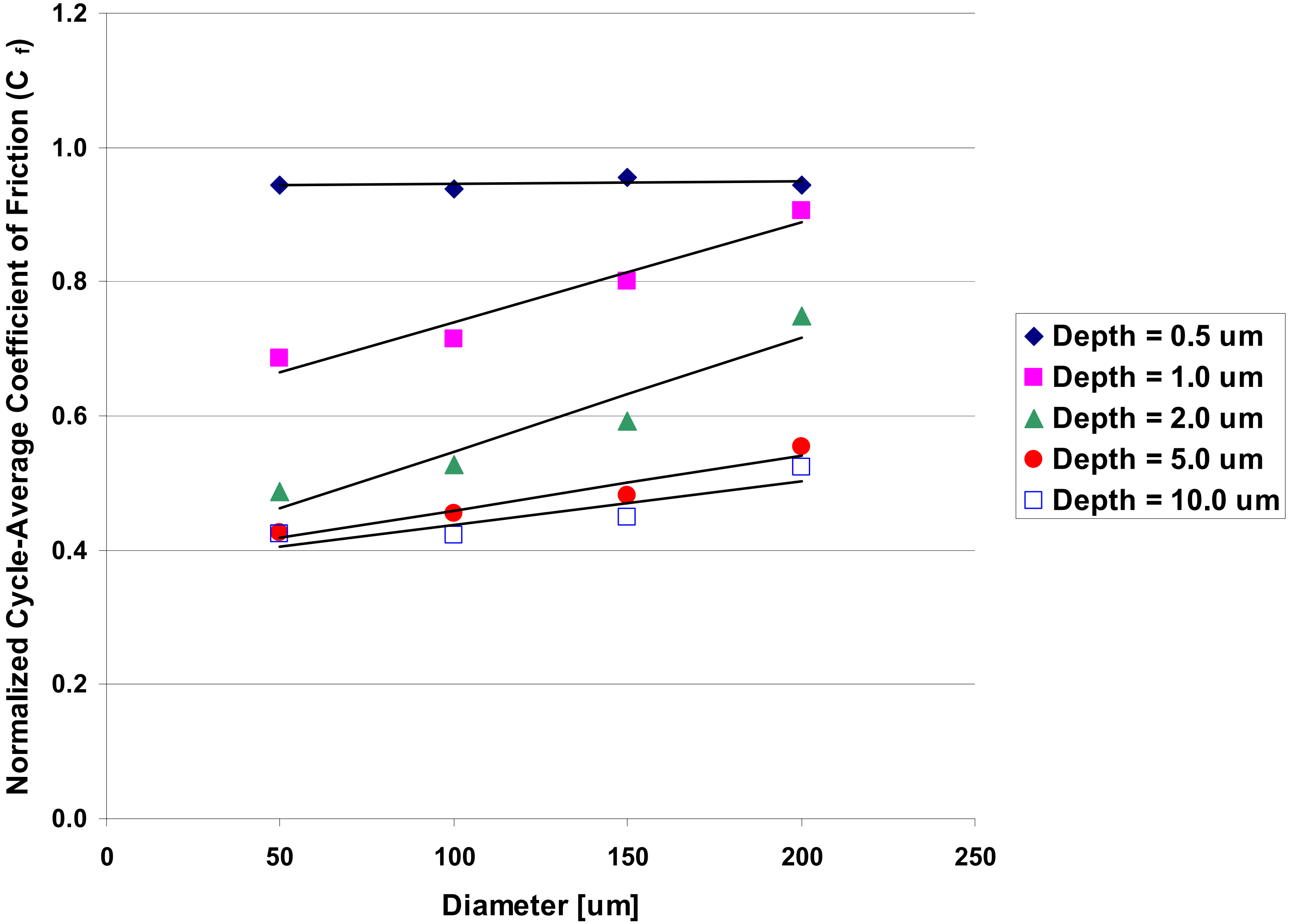
- Dimples: 100mm wide by 1mm deep, 13% Area Coverage
- Modifications applied to the ring have blunted the friction spikes
- Dimples applied to the liner are more effective at reducing the friction
- Motion of the dimples through the contact zone causes fluctuation in the viscous friction contribution

Effect of Dimple Geometry

13% Area Coverage

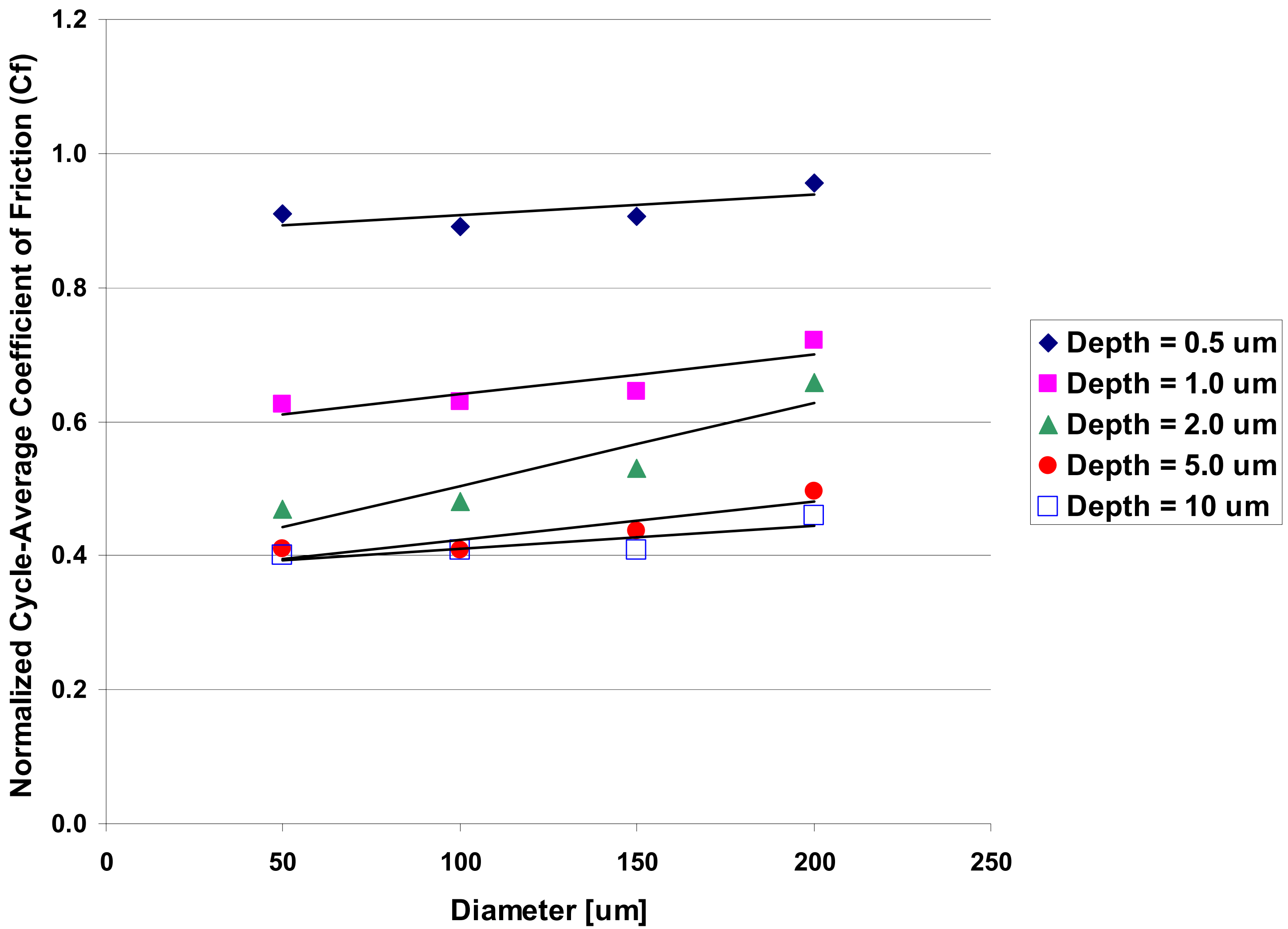


Effect of Dimple Geometry
25% Area Coverage



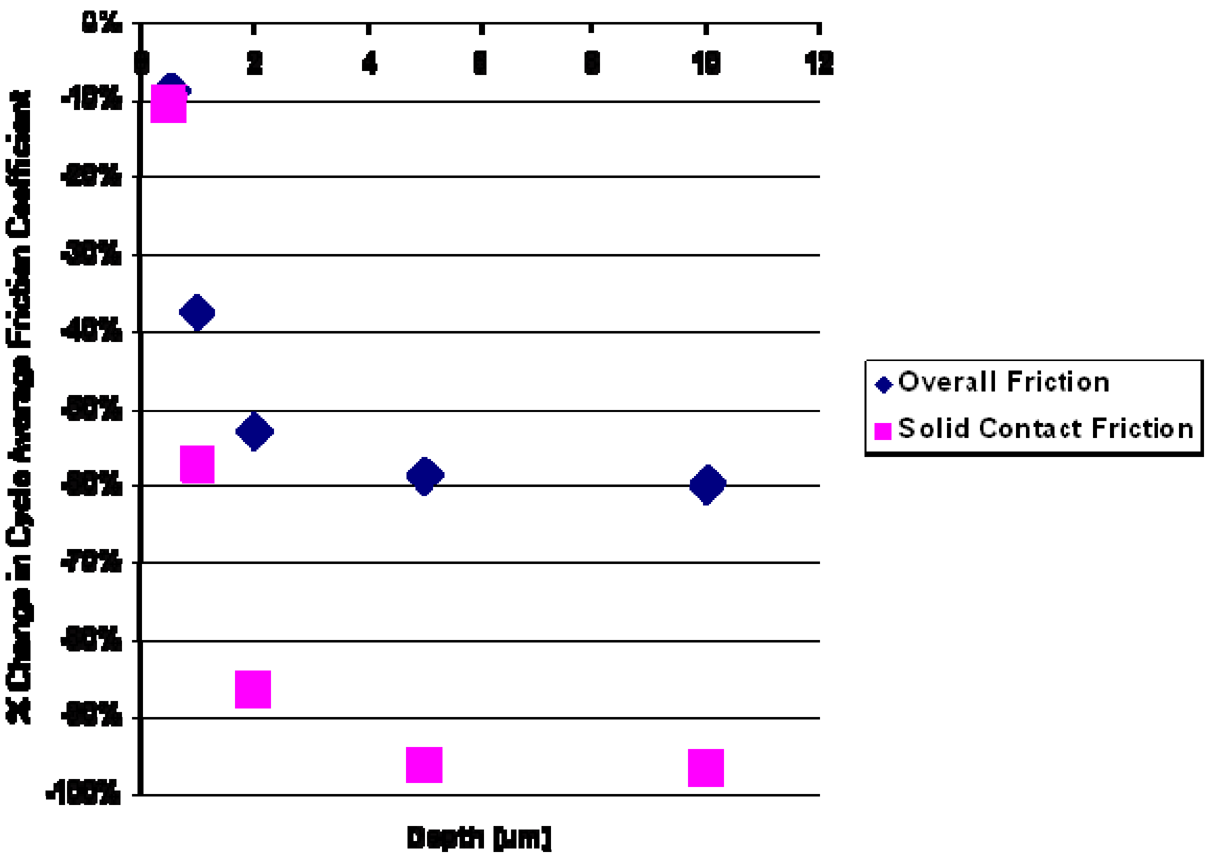
Effect of Dimple Geometry

50% Area Coverage



Friction Reduction Limitations (Effect of Dimple Depth)

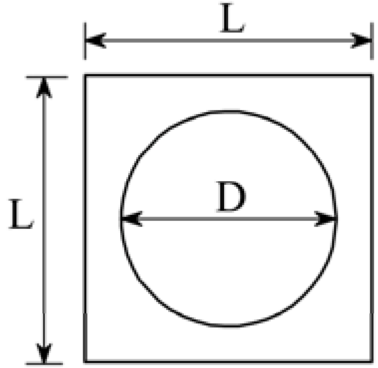
50 µm diameter, 50% coverage

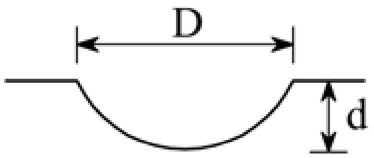


- Friction reduction is realized near TDC/BDC by reducing the amount of asperity interaction
- Viscous shear contribution remains even after solid contact friction has been eliminated

Dimensional Analysis

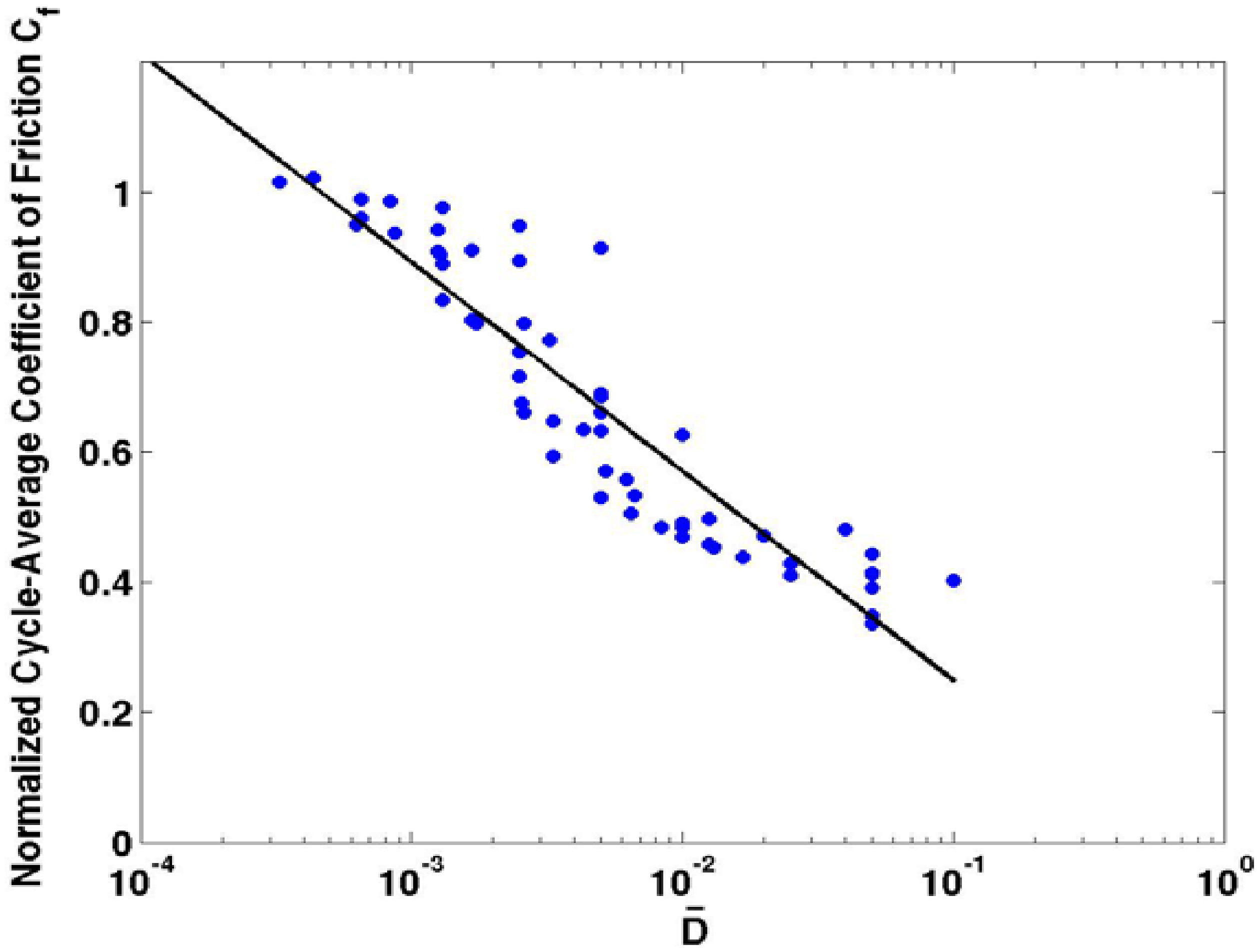
- Dimple diameter, depth, and area coverage can all influence the performance of the modified surface
- Through dimensional analysis, a single dimensionless variable can be developed to describe the effect of dimple geometry on the performance of a modified surface





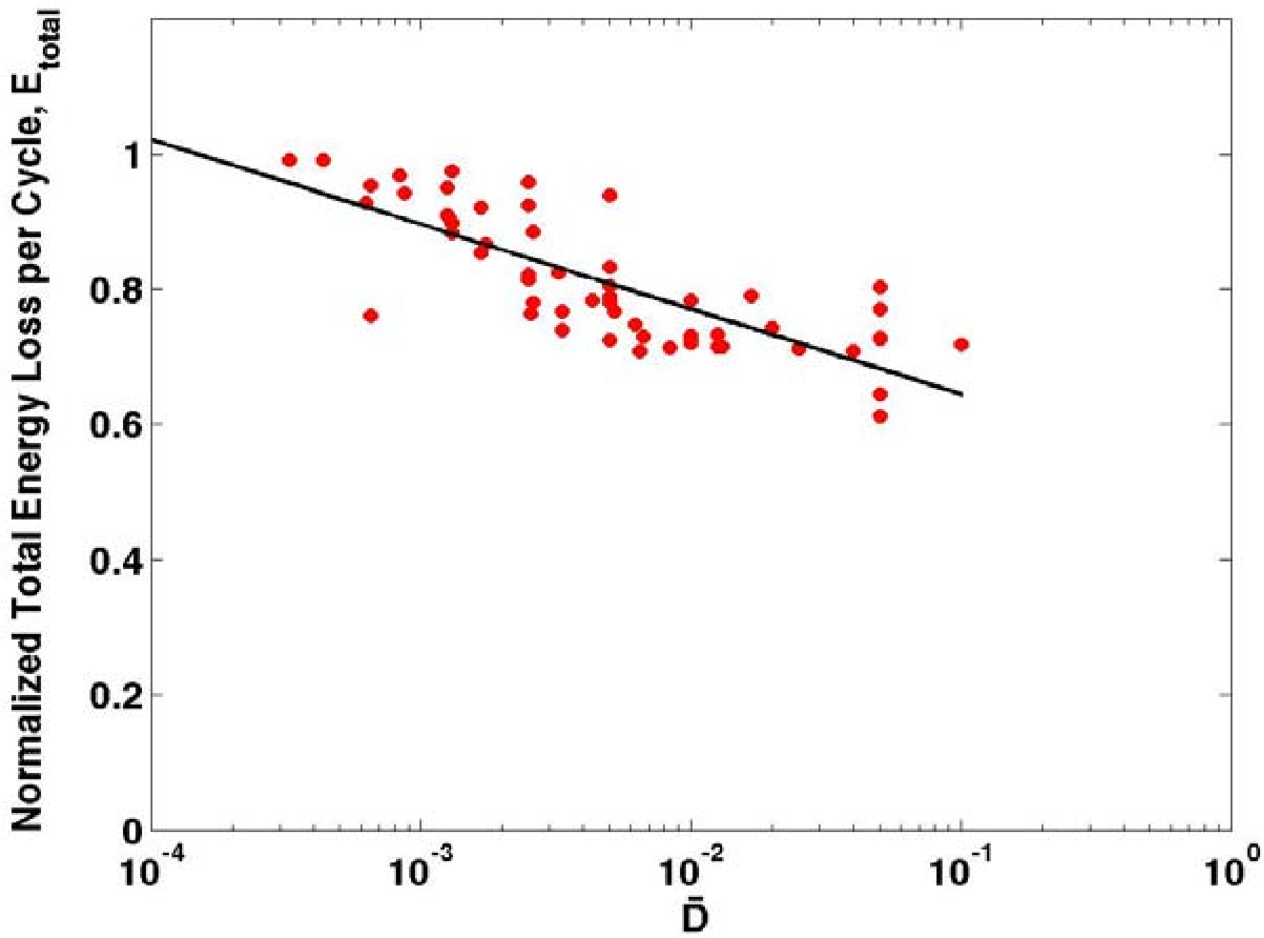
$$\bar{D} = \frac{d}{D} \times \frac{\pi D^2}{4L^2} = \frac{\pi d D}{4L^2}$$

Effect of Surface Modifications on Cycle-Average Coefficient of Friction



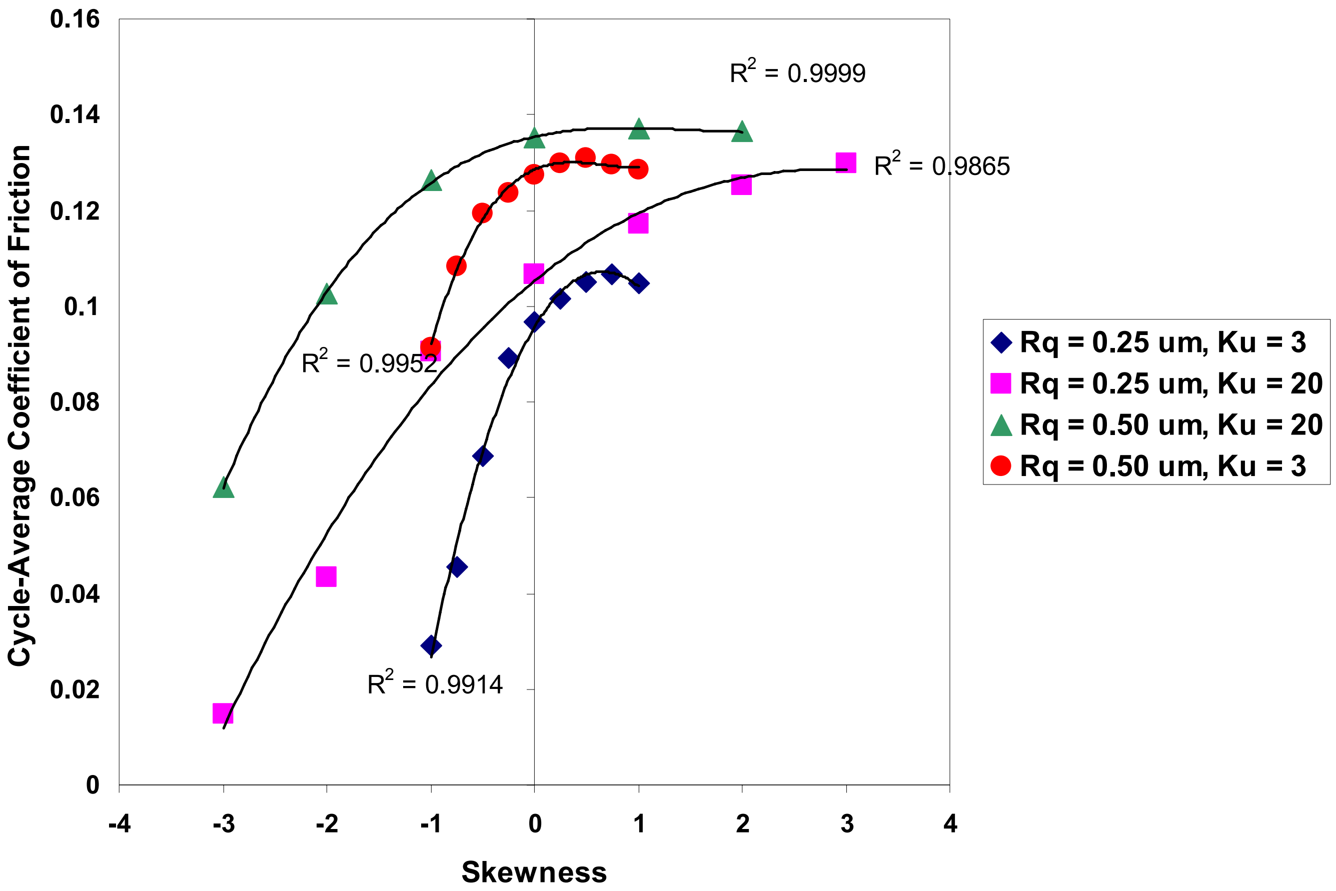
$$\bar{D} = \frac{\pi d D}{4L^2}$$

Effect of Surface Modifications on Total Energy Loss per Cycle



$$\bar{D} = \frac{\pi dD}{4L^2}$$

Effect of Surface Skewness on Cycle-Average Coefficient of Friction



Summary
(Numerical Modeling of Mixed Lubrication)

- **Stochastic**
  - No elastic deformation
  - Asperity contact pressures are estimated using a statistical model (Greenwood & Tripp)
  - Fast, reasonable results for friction and film thickness
  - Cannot easily handle non-Gaussian surfaces or surface patterning
- **Semi-deterministic**
  - No elastic deformation
  - Asperity contact pressure vs. displacement relationship is calculated offline
  - Fast, reasonable results for friction and film thickness once pressure map is calculated
  - Easily handles non-Gaussian surfaces, cannot include surface patterning
- **Fully deterministic**
  - Includes elastic deformation
  - Asperity contact pressure is calculated explicitly
  - Computationally intensive
  - Easily handles non-Gaussian surfaces including surface patterning

Summary

- Mixed lubrication models have been developed and applied to investigate the lubrication and frictional loss at the piston ring/cylinder liner interface
  - Stochastic, Hydrodynamic
  - Semi deterministic, Hydrodynamic
  - Fully Deterministic, Elastohydrodynamic
- There is good correlation between measured and predicted friction and film thickness
- Application of surface modifications to the liner segment is predicted to provide better friction reduction than modifying the piston rings
- Non-Gaussian characteristics of the surfaces must be taken into account in order to accurately predict frictional loss due to asperity contact
- Cycle-average coefficient of friction can be reduced by 55-65%
- Total energy loss per cycle has been reduced by 20-40%

Collaboration with Industry & Technology Transfer

- METL Annual Advisory Group Meeting
  - November 2, 04 @ PU, West Lafayette, IN
    - Attendees: CAT, Cummins, Waukesha, Tecumseh, Timken, FAG, Honeywell, RR, Bosch, SKF, GE, WPAFB, Lubrizol, Nye Lubricants, Raytheon
- DOE-ARES Technical Exchange Meeting
  - March 8, 05 @ PU, West Lafayette, IN
    - Attendees: CAT, Cummins, Waukesha
- METL Meeting with CAT
  - May 26, 05 @ CAT, West Lafayette, IN
    - Attendees: CAT
- DOE-ARES Technical Exchange Meeting
  - Fall 05 to be held @ MIT, Boston, MASS

Project Schedule

Months
Dates

Task 1: Experimental study of Laser Patterned Cylinder Liner and Friction Reduction in Fired Natural Gas Engine

Recruitment of M.S. students

Course Work (M.S. students)

Literature search and familiarization of students to experimental and analytical investigation of piston ring cylinder liner

Design and purchase of laser machining system to allow for profiling the cylinder liner

Design and development of CAD drawings for the Perkins engine dynamometer (PED)

Construction of PED

Evaluation and shake down of PED

Using PED to investigate the effects of surface profiling on friction reduction

Preparation of thesis and dissemination of results to sponsor

Task 2: Analytical Modeling of Friction Control through Surface Modification

Development of models for surface rough surfaces in contact incorporating elastic and plastic deformation of the surface asperities

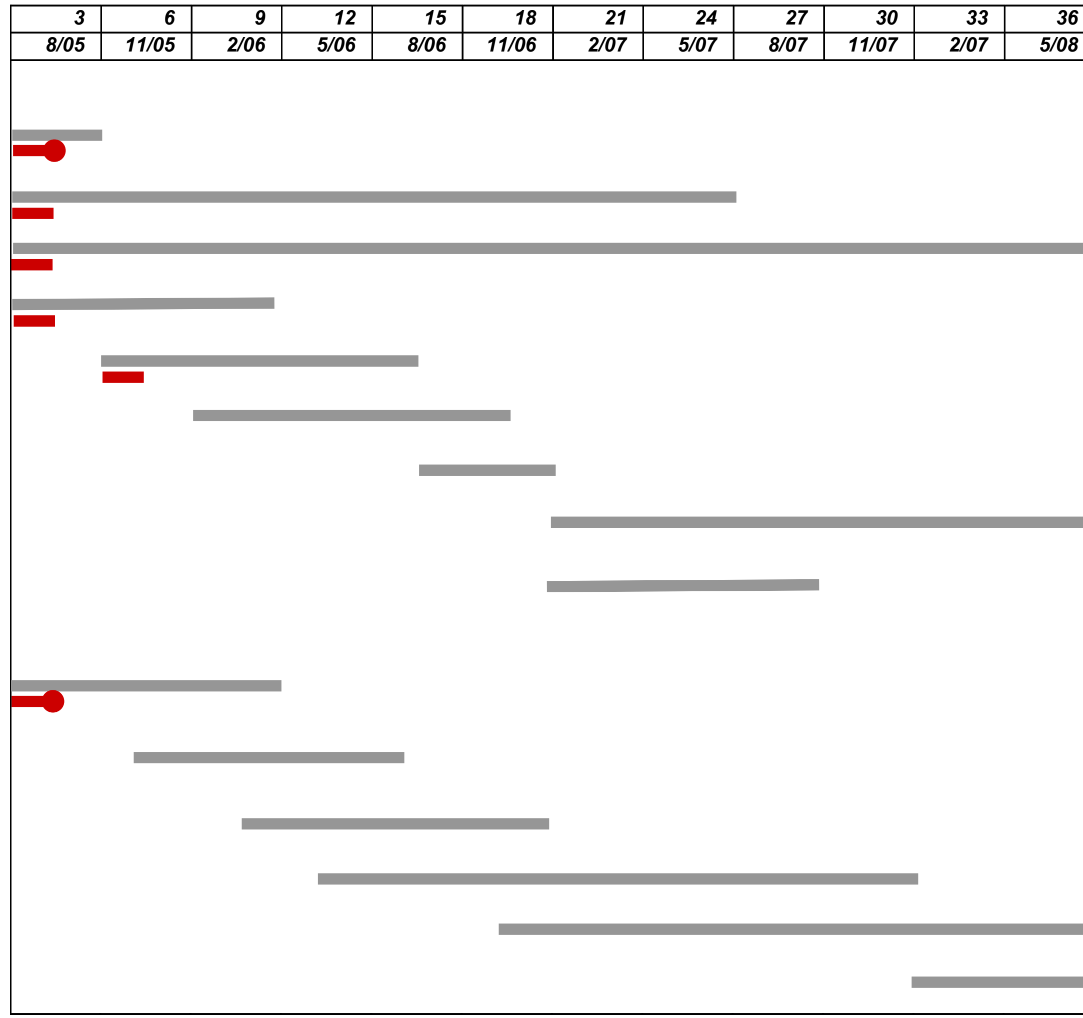
Development of lubrication models for boundary and mixed lubrication regimes operating in the presence of surface features which can plastically deform

Incorporating thermal effects at the PRCL interface

Combining the PRCL model with main and wrist bearing models to develop a complete model for slider crank mechanism

Corroboration of analytical and experimental results

Preparation of theses and dissemination of results to sponsor



Projected Progress Completed

6 Month Plan

- Complete purchase of laser micromachining station
  - Laserod, Inc. Model M1
  - Nd:YAG laser @ 1024nm
  - X/Y/Z/θ positioning
  - Additional optics to enable patterning inside cylinder
- Evaluate laser performance and capabilities
- Determine optimum settings for surface texturing
- Prepare and evaluate modified surfaces using
  - Reciprocating Liner Test Rig
  - Reciprocating Piston Test Rig

Future Work

- Set-up, shakedown of laser
  - Evaluate laser performance and determine optimum settings for dimpling
  - Prepare test specimens
- Evaluation of modified surfaces using
  - Reciprocating Liner Test Rig
  - Reciprocating Piston Test Rig
- Fired Engine Test Rig
  - Purchase and setup dynamometer
  - Obtain baseline and modified engine performance

- Continue investigation of dimple fundamentals using deterministic mixed lubrication model
  - Rolling Point Contact
  - Sliding Point Contact
- Extend lubrication models to the complete slider crank mechanism
  - Treat the slider crank as a dynamic system of lubricated bodies