
Fluid Film Bearing Analysis:

Navier-Stokes Equations

vs.

Reynolds Equation

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Presentation Overview

➤ Objective

- Illustrate Difference Between Governing Equation Options
 - » Navier-Stokes (N-S)
 - » Reynolds Equation (ReEq)

➤ Methodology

- Presentation will Focus on Select Bearing Analysis Results
 - » Prediction of Journal Location within its Bore
 - Dynamic Coefficients are Directly Related to Journal Location
 - » Various Flow Conditions
 - Highly Laminar to Fully Turbulent
- Presentation is Not Going to Cover the Math
 - » Math is Well Documented in Many Sources, including:
 - Fluid Film Lubrication Theory & Design by Andres Z. Szeri, 1998

Table of Contents

➤ Background

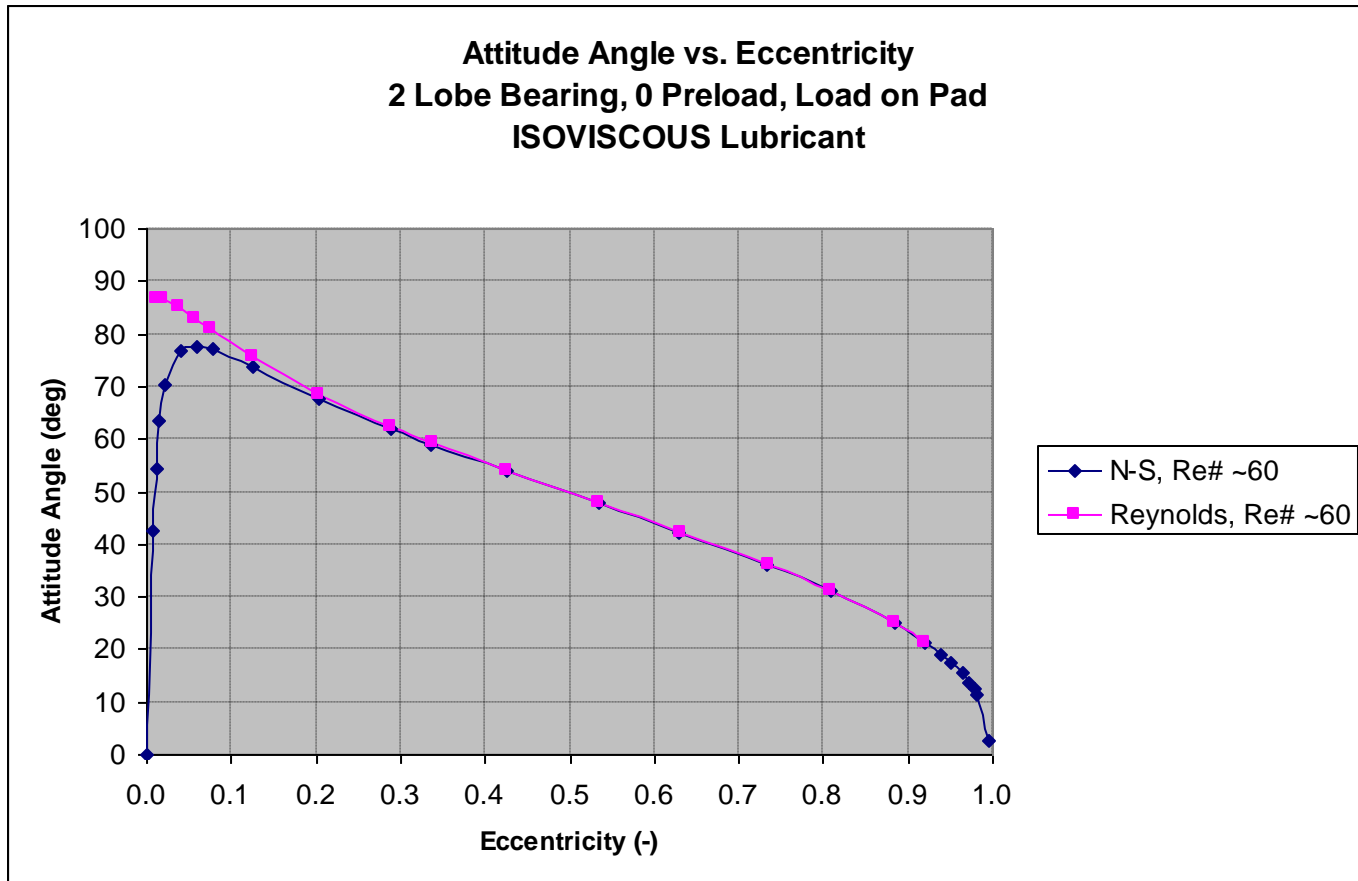
- Reynolds Equation is Derived From the N-S Equations by Making Simplifying Assumptions
 - » Primary Assumption: Neglect Inertia Effects
- Implications of Ignoring Inertia
 - » Eliminates Momentum Equations
 - Primary Advantage:
 - Greatly Simplifies Solution
Faster Runs, Simpler Solution Algorithm
 - Primary Disadvantage:
 - Loss of Ability to Accurately Model Basic Bearing Effects
 - Shear Stress
 - Turbulence
 - Rotor Speed
 - Surface Roughness
 - Fluid Compressibility
 - Non-Newtonian Fluids
 - Low Eccentricity Bearings

Sample Calculations: Set 1

➤ Journal Bearing Analysis

- 2 Lobe Fixed Geometry Bearing
 - » Circular Bore (Zero Preload)
 - » Load on Pad
 - » Isoviscous Lubricant
 - » Rotor Diameter = 2 inches
 - » Rotor Speed = 10000 rpm
- **Maximum Reynolds Number (Re#) on Loaded Bearing Surface: ~60**

Highly Laminar Flow Results



Highly Laminar Flow Results

➤ Journal Bearing Analysis: Max. Re# ~60

- Discussion of Results:

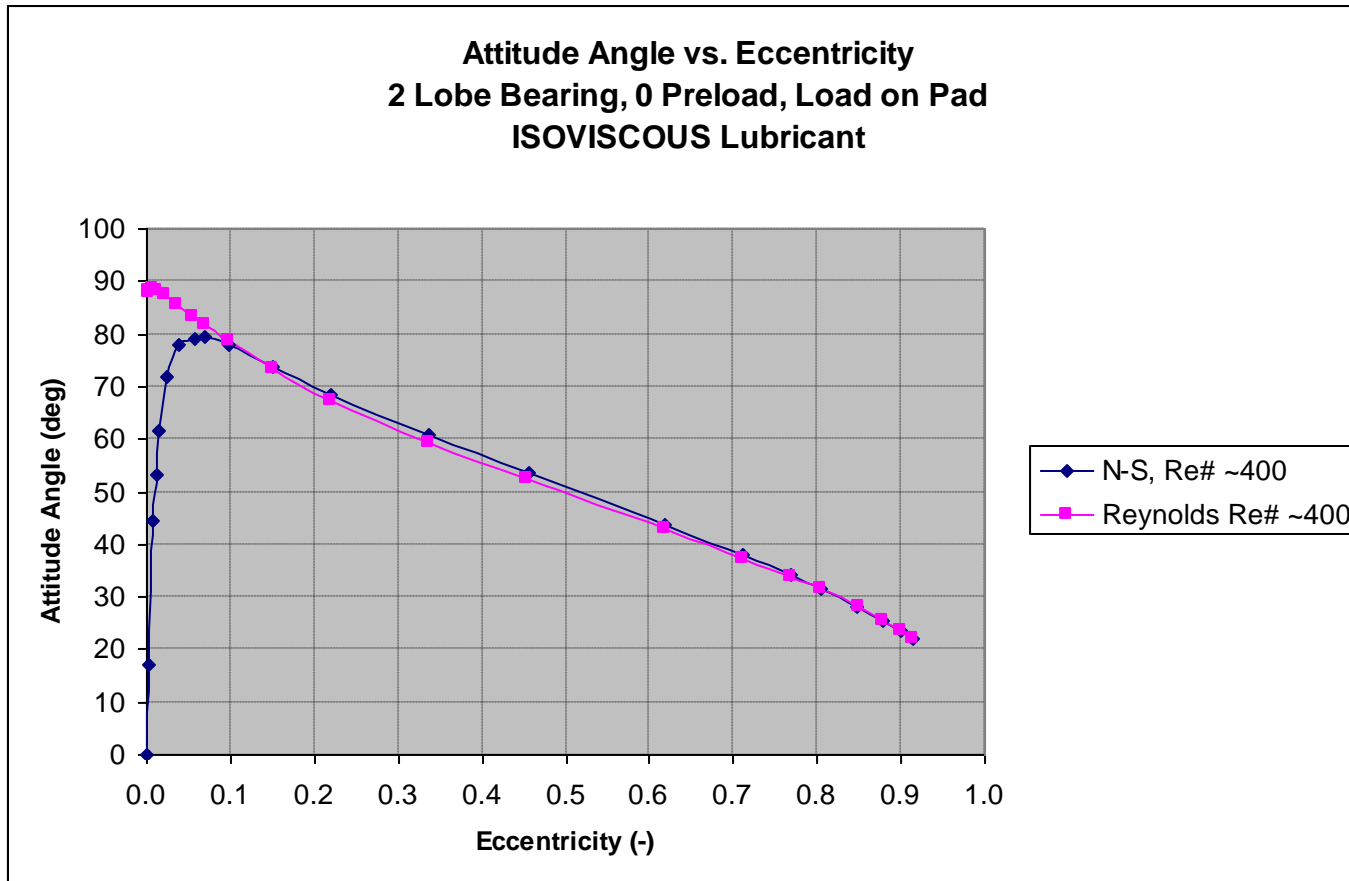
- » **Note: All Data Points Shown are For Identical Applied Loads**
- » Reynolds Equation Results Are Virtually Identical N-S Results For Operating Conditions that Yield High Journal Eccentricities ($e > 50\%$) & Highly Laminar Flow
- » Inertia Affects the Solution For Operating Conditions that Yield Low Journal Eccentricities ($e < 50\%$) & Highly Laminar Flow
 - $e < 20\%$: Inertia Effects are Significant
 - $e < 10\%$: Inertia Effects Dominate the Solution

Sample Calculations: Set 2

➤ Journal Bearing Analysis

- 2 Lobe Fixed Geometry Bearing
 - » All Conditions Identical to Set 1 Calculations Except Rotor Speed
 - » Rotor Speed = 60000 rpm
- **Maximum Re# on Loaded Bearing Surface: ~400**

Laminar Flow Results



Laminar Flow Results

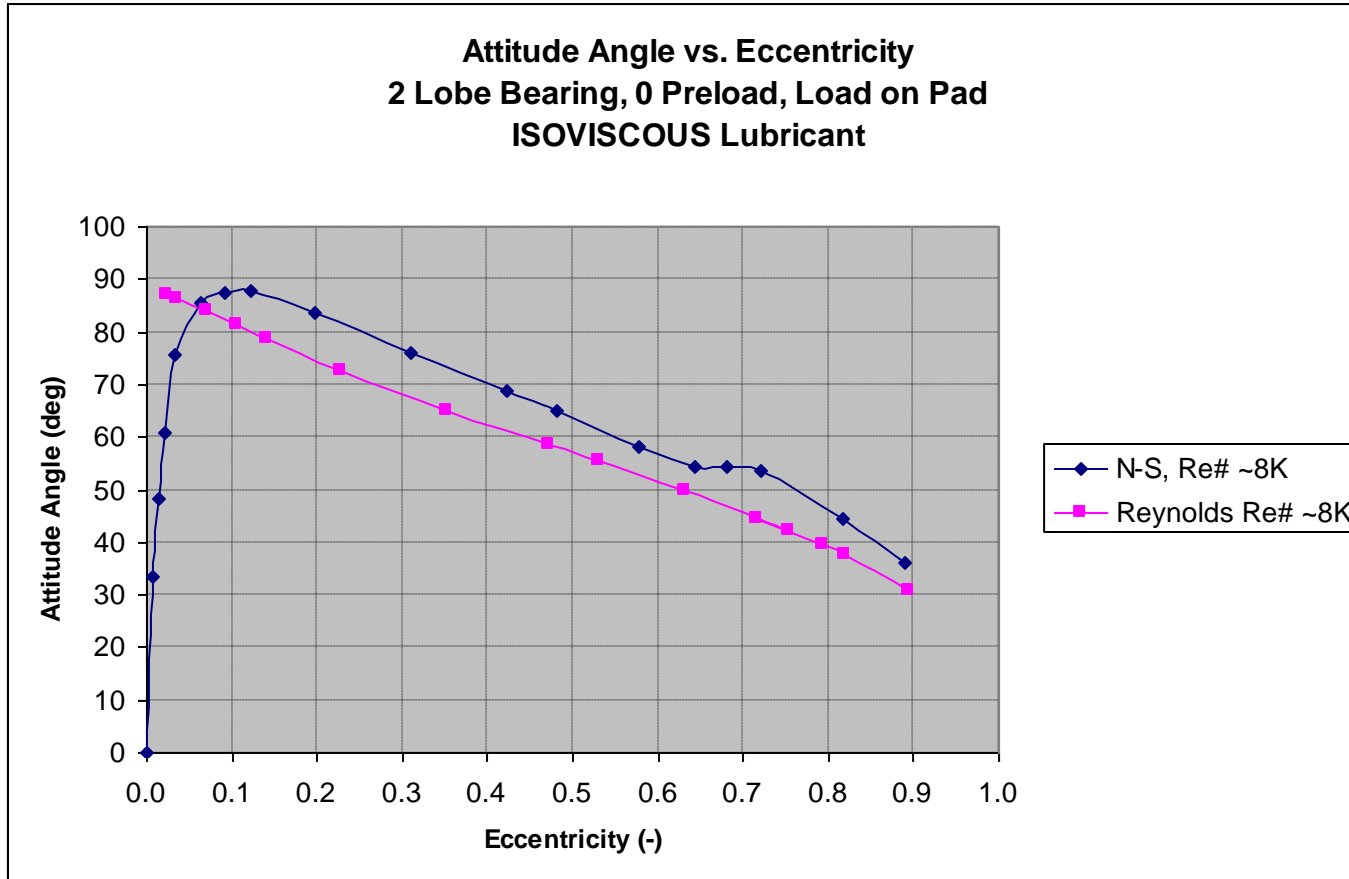
- **Journal Bearing Analysis: Max. Re# ~400**
 - **Discussion of Results:**
 - » **Note: All Data Points Shown are For Identical Applied Loads**
 - » **Reynolds Equation Results Are Nearly Identical to N-S Results For Operating Conditions that Yield High Journal Eccentricities ($e > 75\%$) & Laminar Flow**
 - » **Inertia Affects the Solution For Operating Conditions that Yield Low Journal Eccentricities ($e < 75\%$) & Laminar Flow**
 - $e < 60\%$: Inertia Effects are Significant
 - $e < 10\%$: Inertia Effects Dominate the Solution

Sample Calculations: Set 3

➤ Journal Bearing Analysis

- 2 Lobe Fixed Geometry Bearing
 - » All Conditions Identical to Set 1 Calculations Except Rotor Speed and Viscosity
 - » Rotor Speed = 40000 rpm
- Maximum Re# on Loaded Bearing Surface: ~8000

Transitional Flow Results



Transitional Flow Results

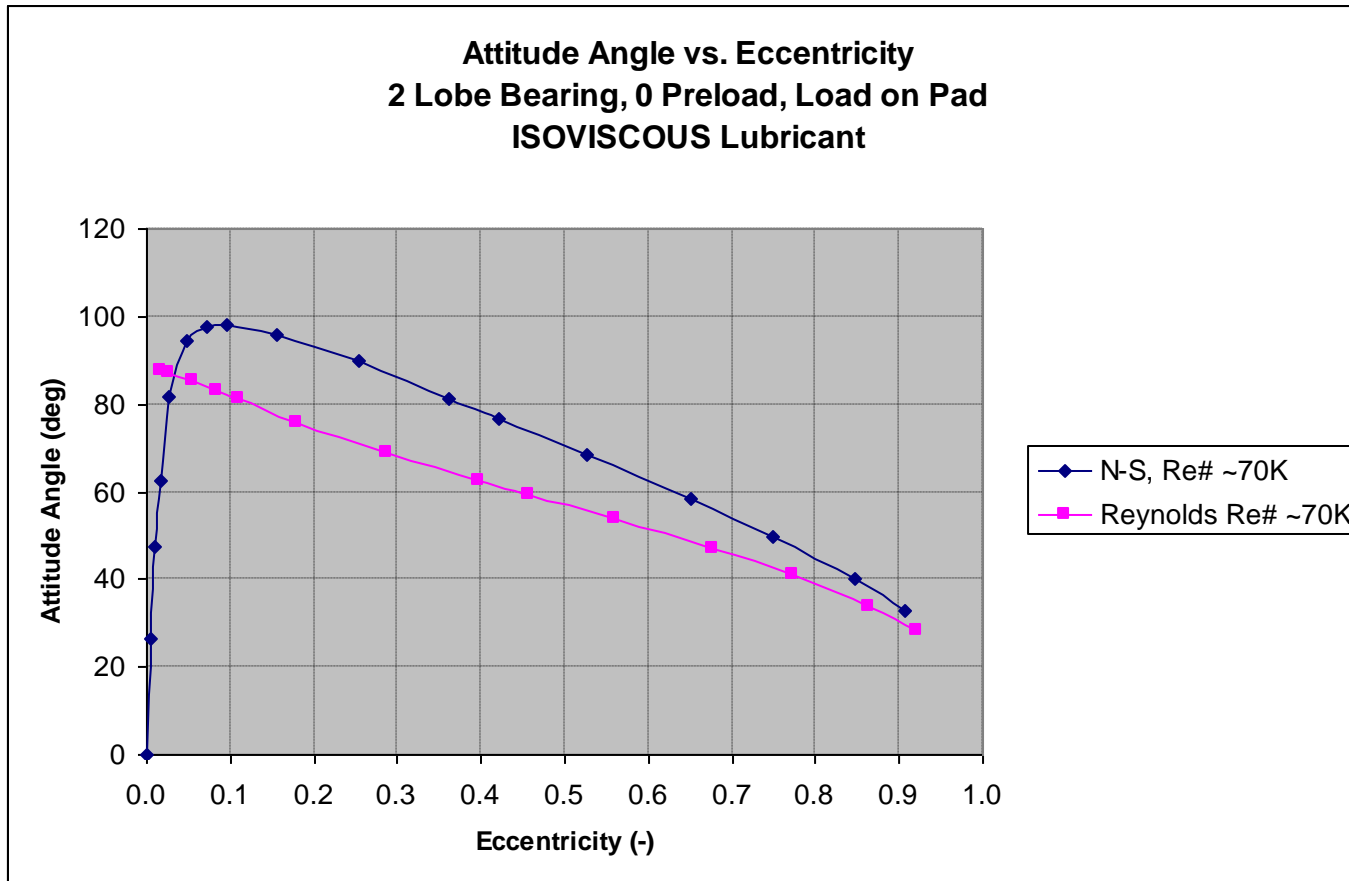
- **Journal Bearing Analysis: Max. Re# ~8000**
 - **Discussion of Results:**
 - » **Note: All Data Points Shown are For Identical Applied Loads**
 - » **Reynolds Equation Inaccurate At All Eccentricities**
 - **Results Only In the Ball Park for The Two Highest Eccentricity Cases ($e > 80\%$)**
 - » **Inertia Effects Substantial At All Eccentricities**

Sample Calculations: Set 4

➤ Journal Bearing Analysis

- 2 Lobe Fixed Geometry Bearing
 - » All Conditions Identical to Set 1 Calculations Except Rotor Speed and Viscosity
 - » Rotor Speed = 60000 rpm
- **Maximum Re# on Loaded Bearing Surface: ~70000**

Fully Turbulent Flow Results



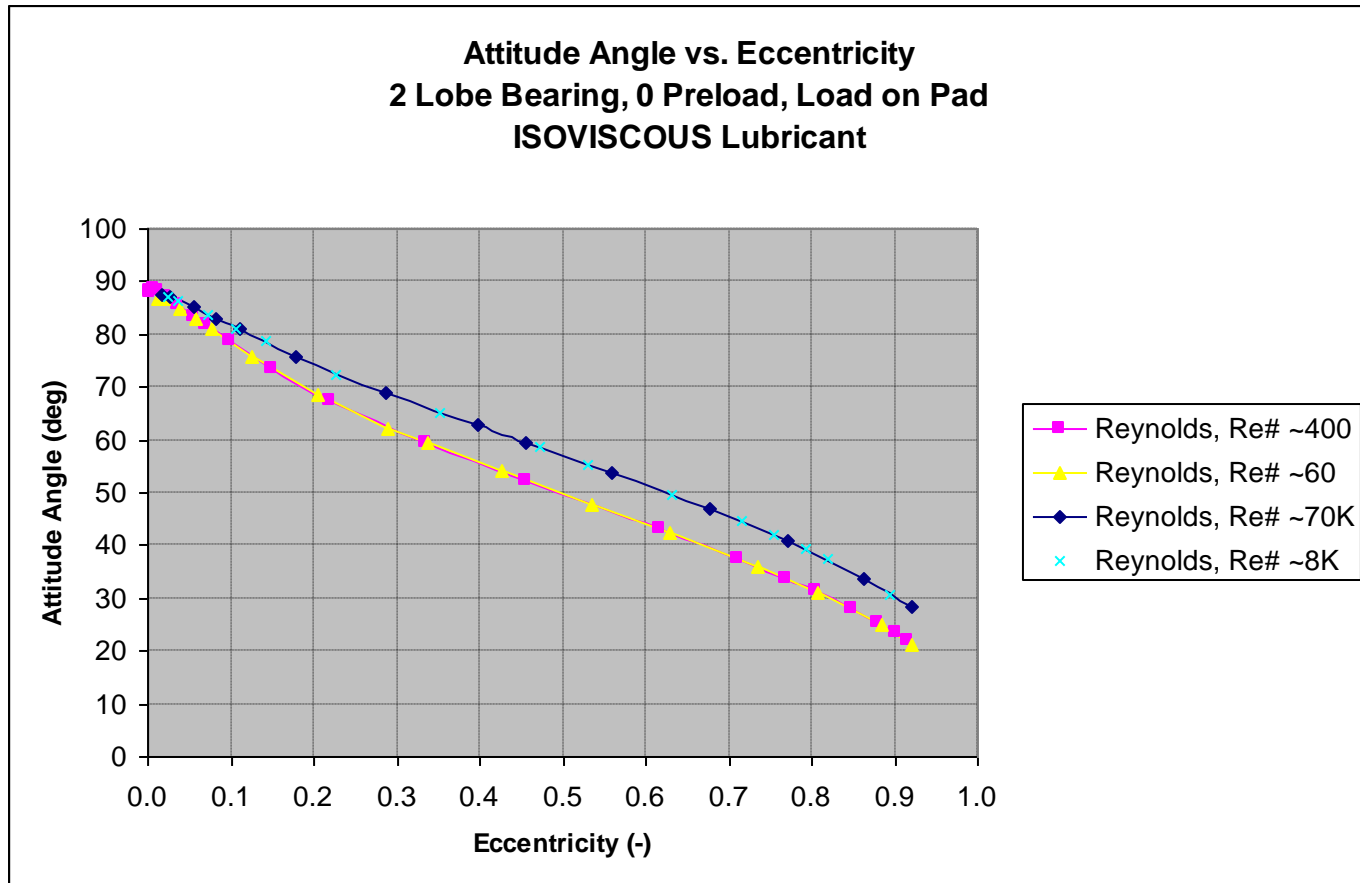
Fully Turbulent Flow Results

- **Journal Bearing Analysis: Max. Re# ~70000**
 - **Discussion of Results:**
 - » **Note: All Data Points Shown are For Identical Applied Loads**
 - » **Reynolds Equation Inaccurate At All Eccentricities**
 - **Results Only In the Ball Park for The Two Highest Eccentricity Cases ($e > 80\%$)**
 - » **Inertia Effects Substantial At All Eccentricities**

Reynolds Equation Summary

- All Reynolds Equation Analysis Results (Fixed Geometry) are Plotted On the Following Page
 - Review of the Plot Shows:
 - » Reynolds Equation Offers a Binary Solution
 - Flow is Laminar (lower curve) or Turbulent (higher curve)
 - Locus of Centers, Regardless of Geometry or Operating Conditions, Will Fall on One of the Two Curves
 - Location on Curve Based Upon Sommerfeld Number (viscosity, diameter, length, load, clearance, and speed)
 - » Reynolds Equation Implicitly Assumes Away the Non-Linear Relationship Between Reynolds Numbers and Rotational Speed (i.e. ROTOR SPEED AND FLOW CONDITIONS DO NOT MOVE THE CURVES)

Reynolds Equation Summary



Navier-Stokes Summary

➤ **All Navier-Stokes Equations Analysis Results (Fixed Geometry) are Plotted On the Following Page**

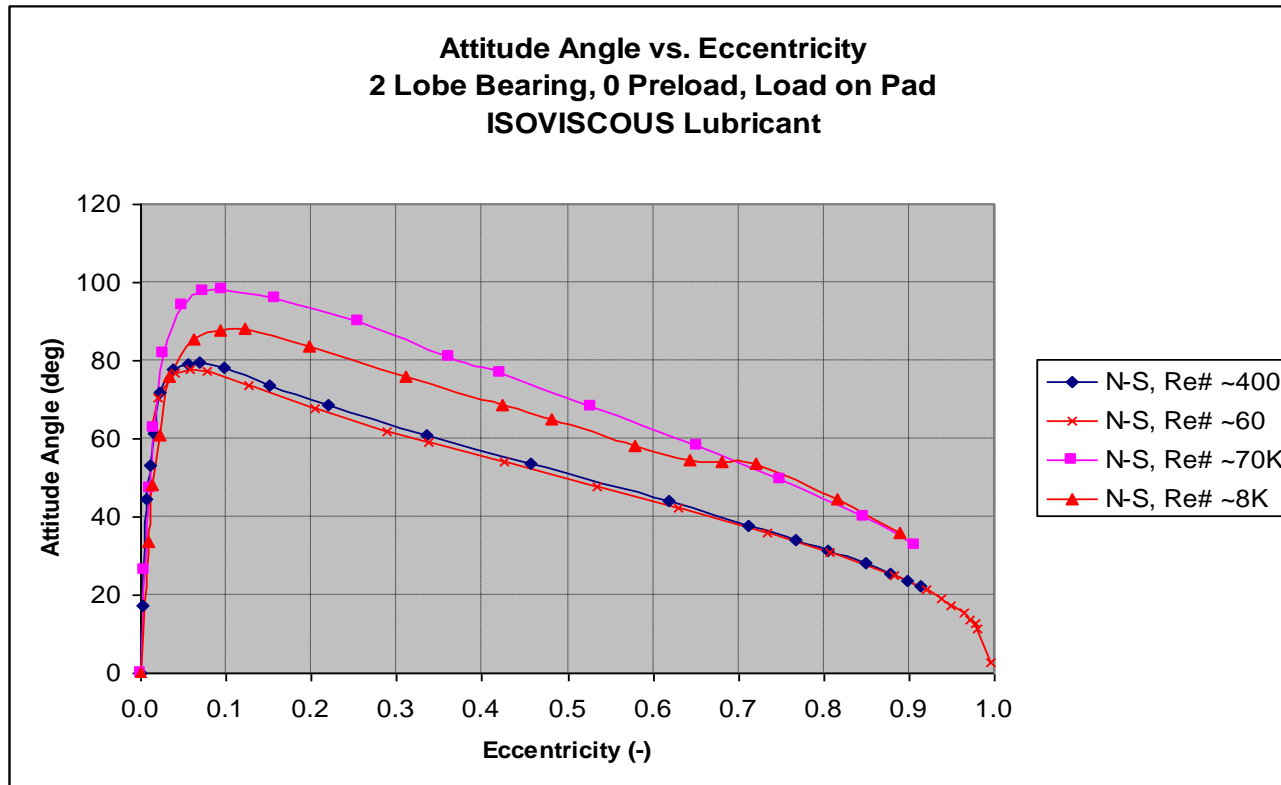
- **Review of the Plot Shows:**

- » **Navier-Stokes Equations are NOT a Binary Solution**

- **Inertia Related Non-Linearities Prevalent Even in Laminar Flow**
- **Capable of Capturing Laminar to Turbulent Transitional Effects**
 - **Note Such Effects Persist Up to $Re\# \sim 10000$**
- **Locus of Centers Curve Shape Determined Uniquely for Set of Geometry/Operating Conditions Analyzed**
 - **Curve May Assume Any Path Between the Fully Laminar and Fully Turbulent Flow Bounds**

- » **Navier-Stokes Based Solution Implicitly Embodies a Non-Linear Relationship Between Reynolds Number and Rotor Speed (i.e. ROTOR SPEED AND FLOW CONDITIONS MOVE THE CURVES)**

Navier-Stokes Summary



Summary

- Reynolds Equation Based Bearing Analysis Only Agrees with N-S Based Analysis Under Certain Circumstances
 - Low Rotational Speeds ($< \sim 10000$ rpm) **AND**
 - Low Reynolds Numbers ($< \sim 60$) **AND**
 - Operating Conditions that Yield Eccentricities $> 50\%$
- Reynolds Equation Based Bearing Analysis **MAY DIFFER RADICALLY** from N-S Based Solutions Under All Other Flow and Operating Conditions

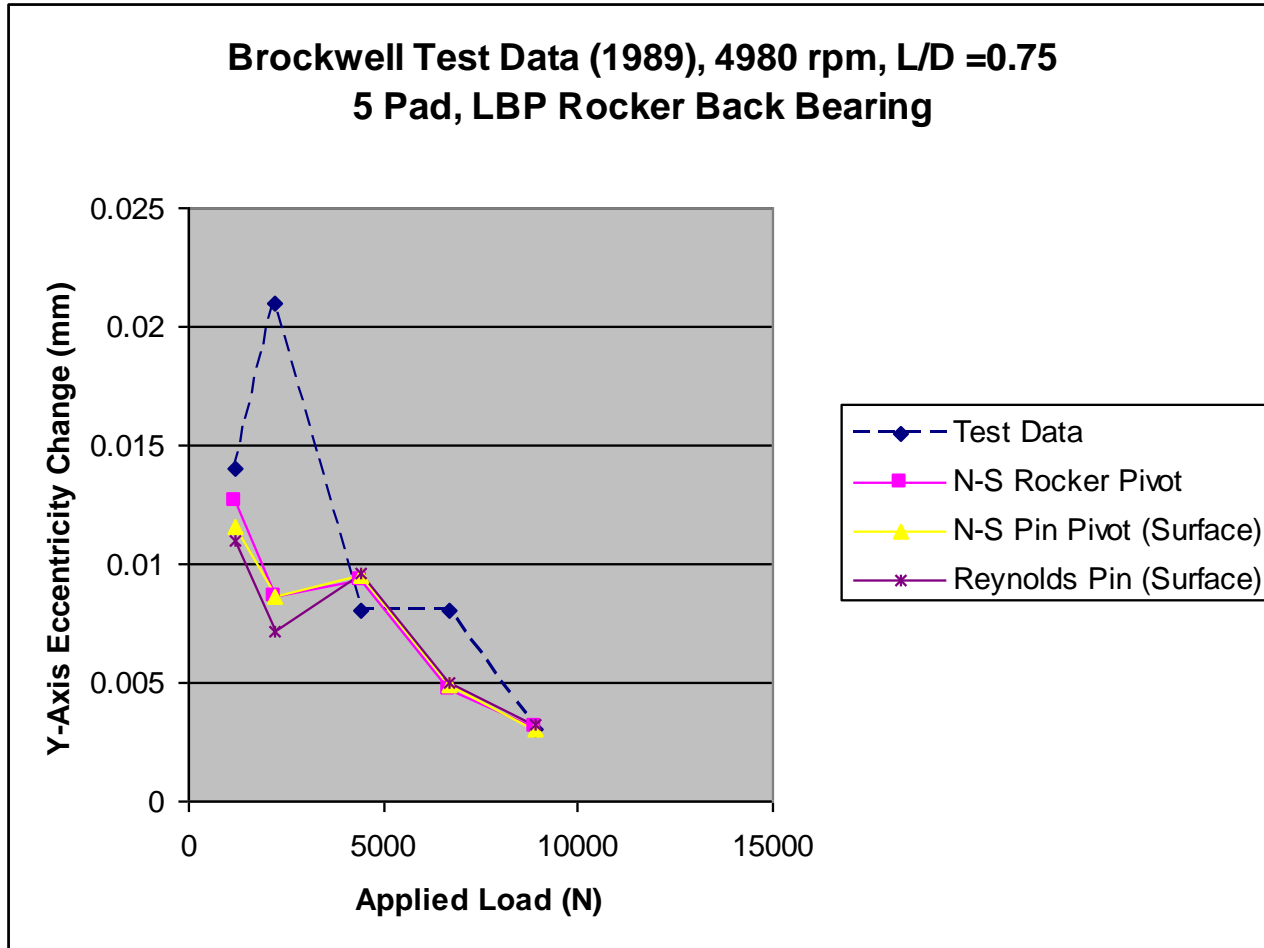
Tilt Pad Bearing Analysis

- Utilizes the Same N-S Stokes Film Solver as Fixed Geometry Bearings
 - Additional Iteration Loop Employed to Solve Pad Positions

- Pivot Models
 - Most Codes Assume Pads Rotate About a Point on the Load Bearing Surface
 - RSR has Implemented Advanced Pivot Models to More Accurately Represent the Motion of the Pad
 - » Pin Pivot
 - » Rocker Back
 - » Ball/Socket

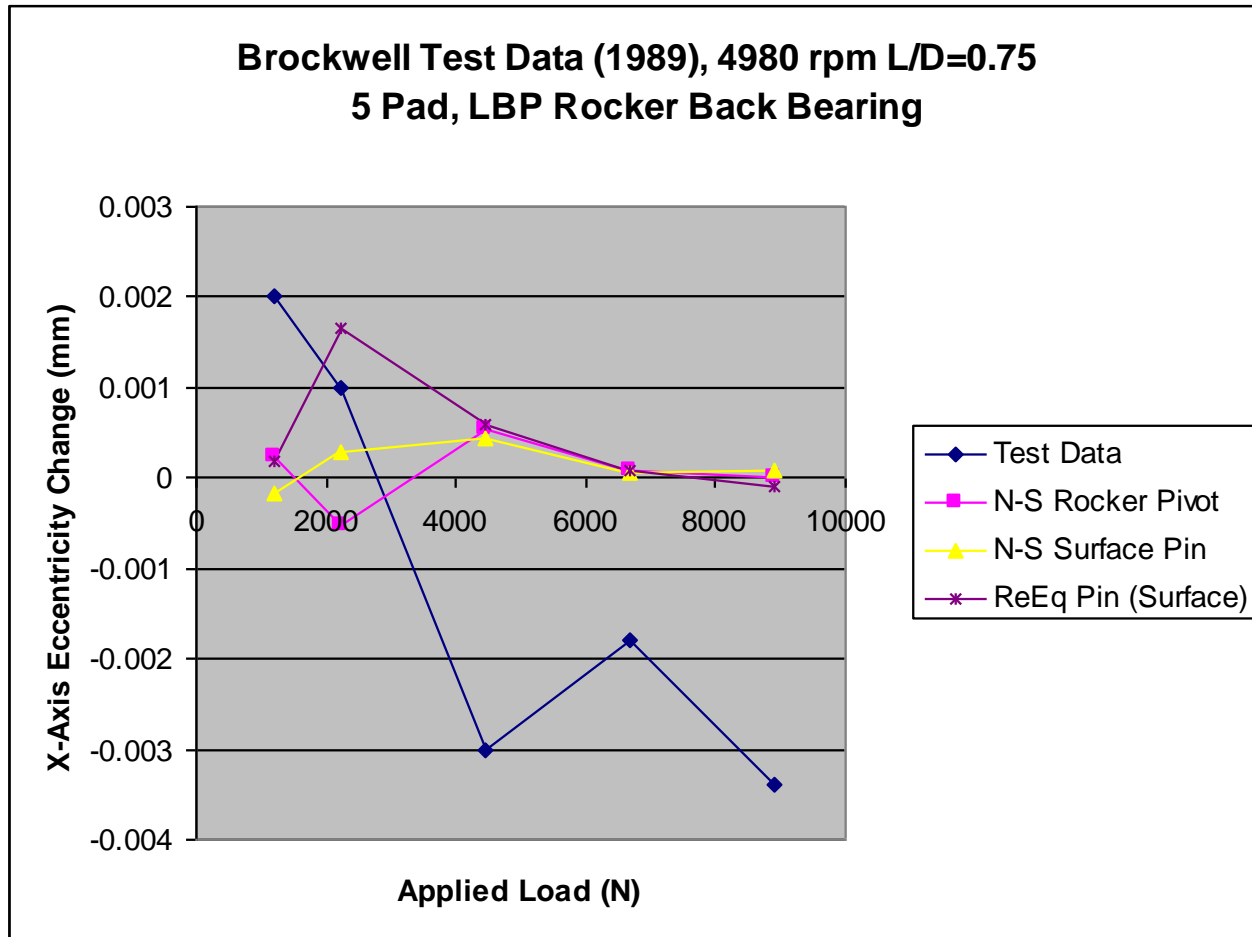
- Sample Analysis Conducted to Match Test Data
 - 5 Pad, Rocker Back Bearing with Load Between Pads

Tilting Pad Test Data Comparison



Reference: Measurements of the Steady State Operating Characteristics of the Five Shoe Tilting Pad Journal Bearing, K.R. Brockwell and D. Kleinbub, Tribology Transactions, 1989, pg 267-275

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Tilting Pad Test Data Comparison

➤ Notes on Test Data

- Rotor Position Measurement was Sub Optimal
 - » 2 Sets of 2 Proximity Probes at Each End of Bearing
 - » Reported Results are the Average of the Two Readings
- Tests Utilizing 2 Sets of 4 Proximity Probes with Results Reported Independently Would Yield Better Data

➤ Comparison With Test Data

- Maximum Re# on Loaded Pads Varies Between 18 and 45
- Both N-S and ReEq Models Produce Reasonable Results
- N-S Predictions are Superior at Low Eccentricities (<50%)
- N-S with Advanced Pivot Model Provides Superior Predictions at Low Eccentricities (<35%)