Rotordynamic 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

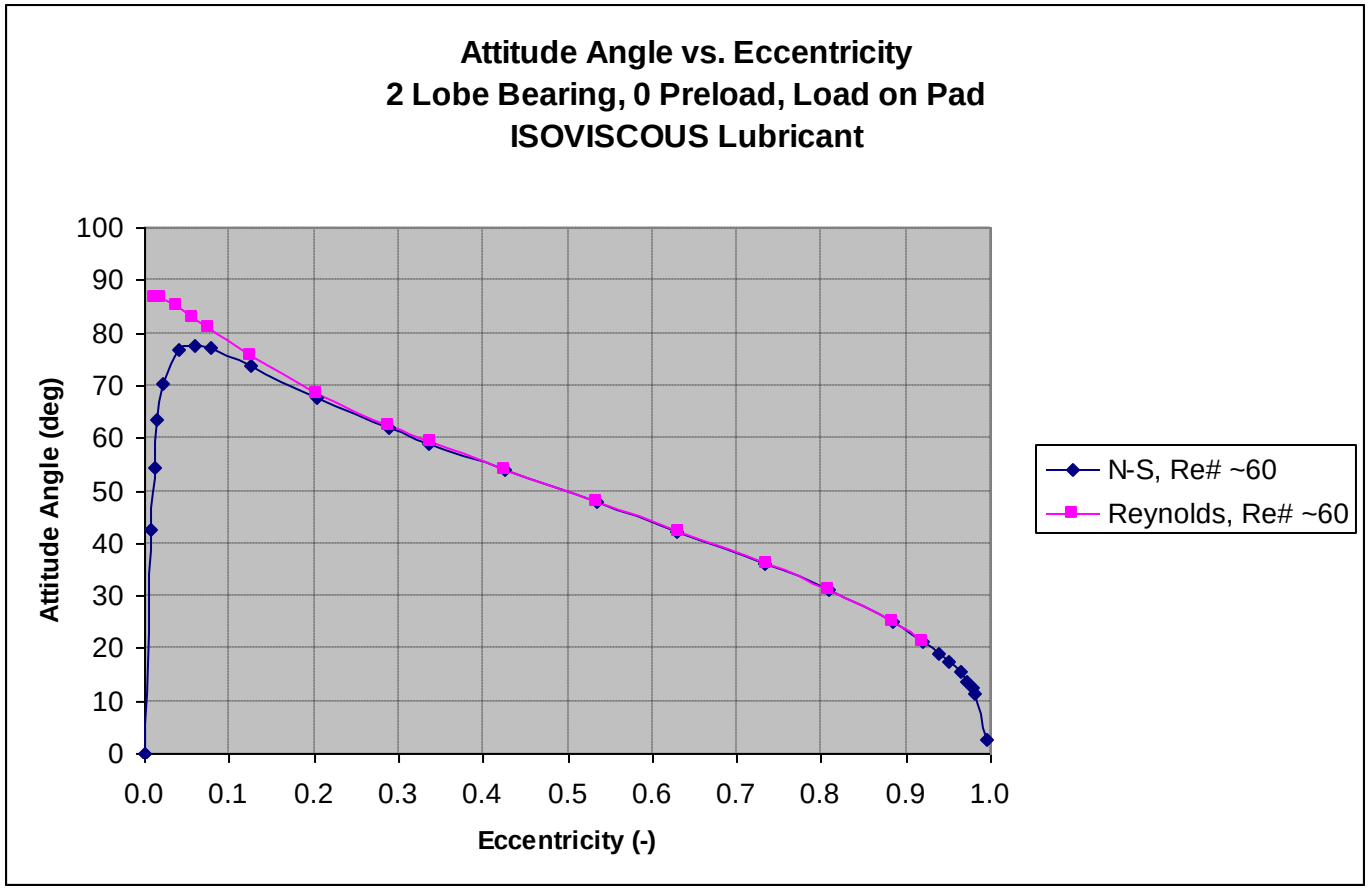
Table of Contents

- 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



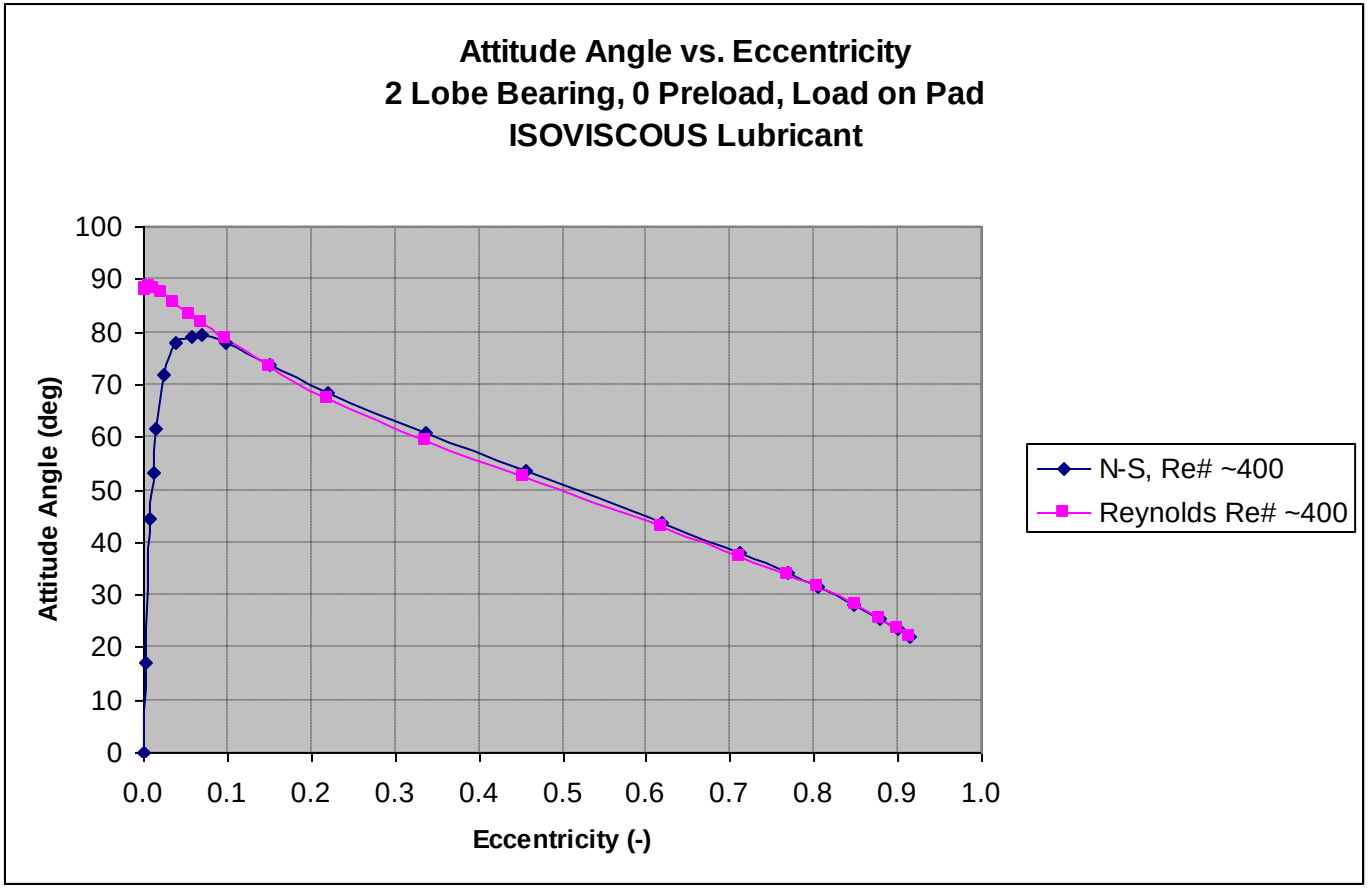
Highly Laminar Flow Results

- **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



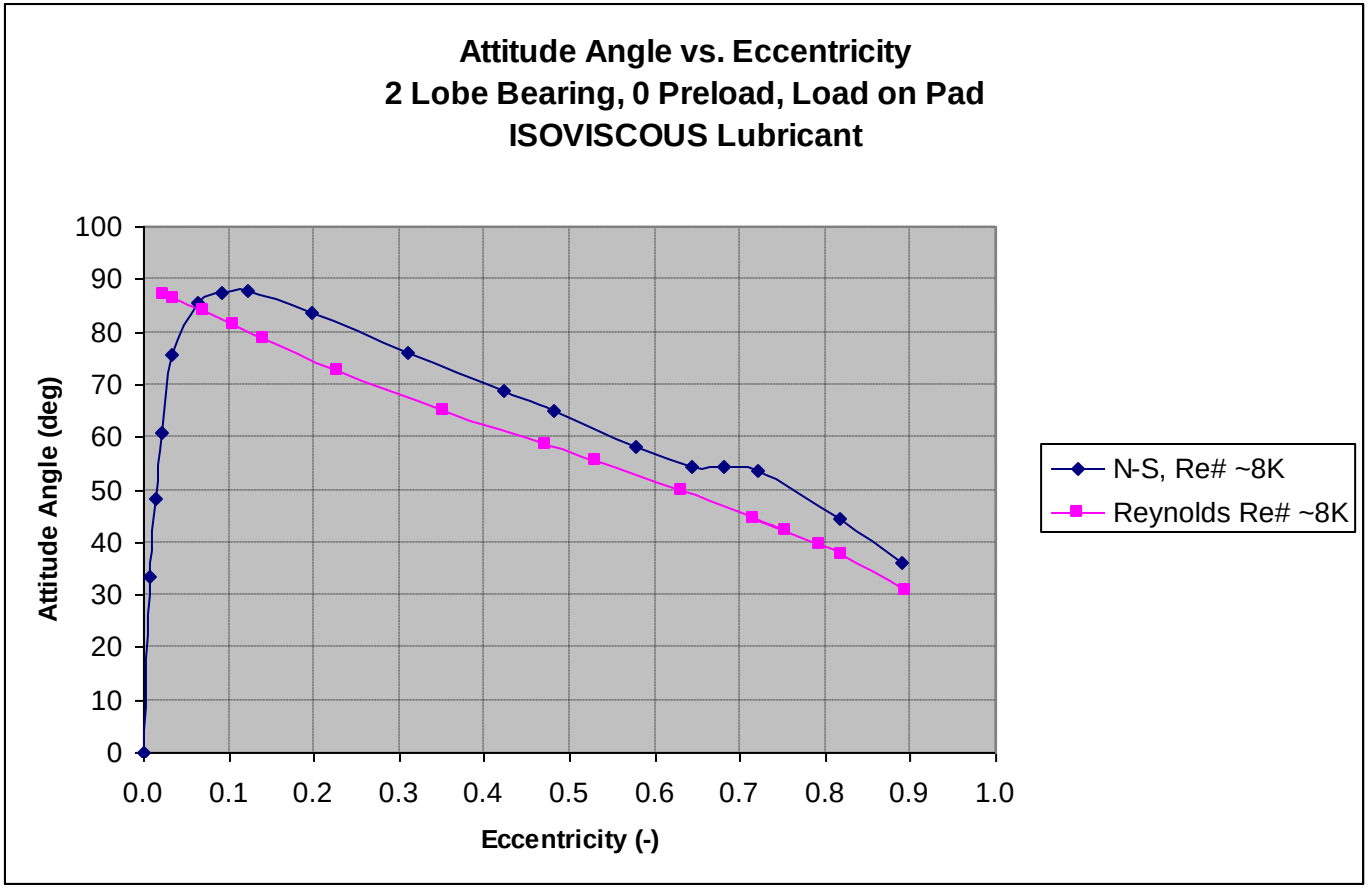
Laminar Flow Results

- **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



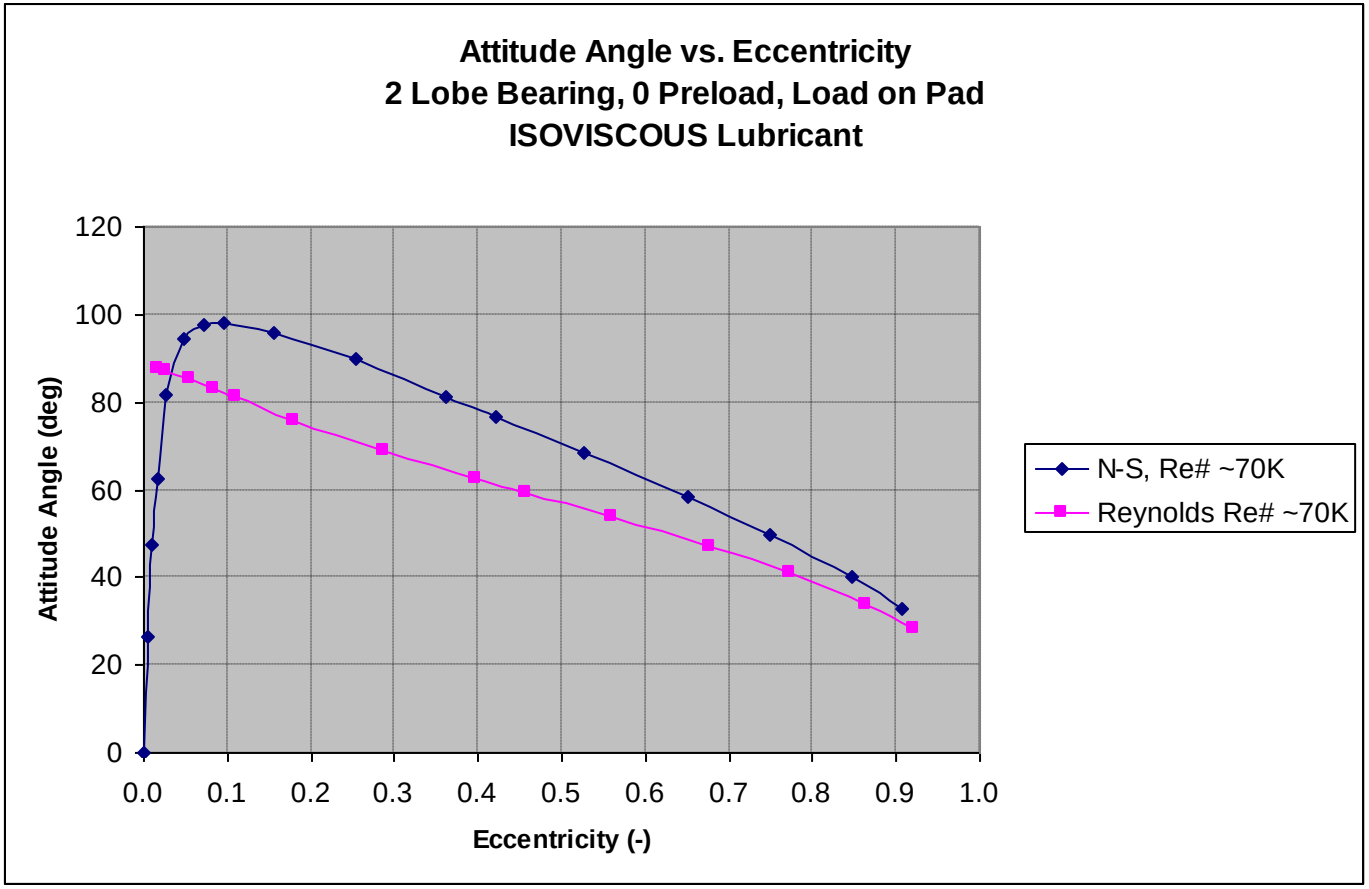
Transitional Flow Results

- **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



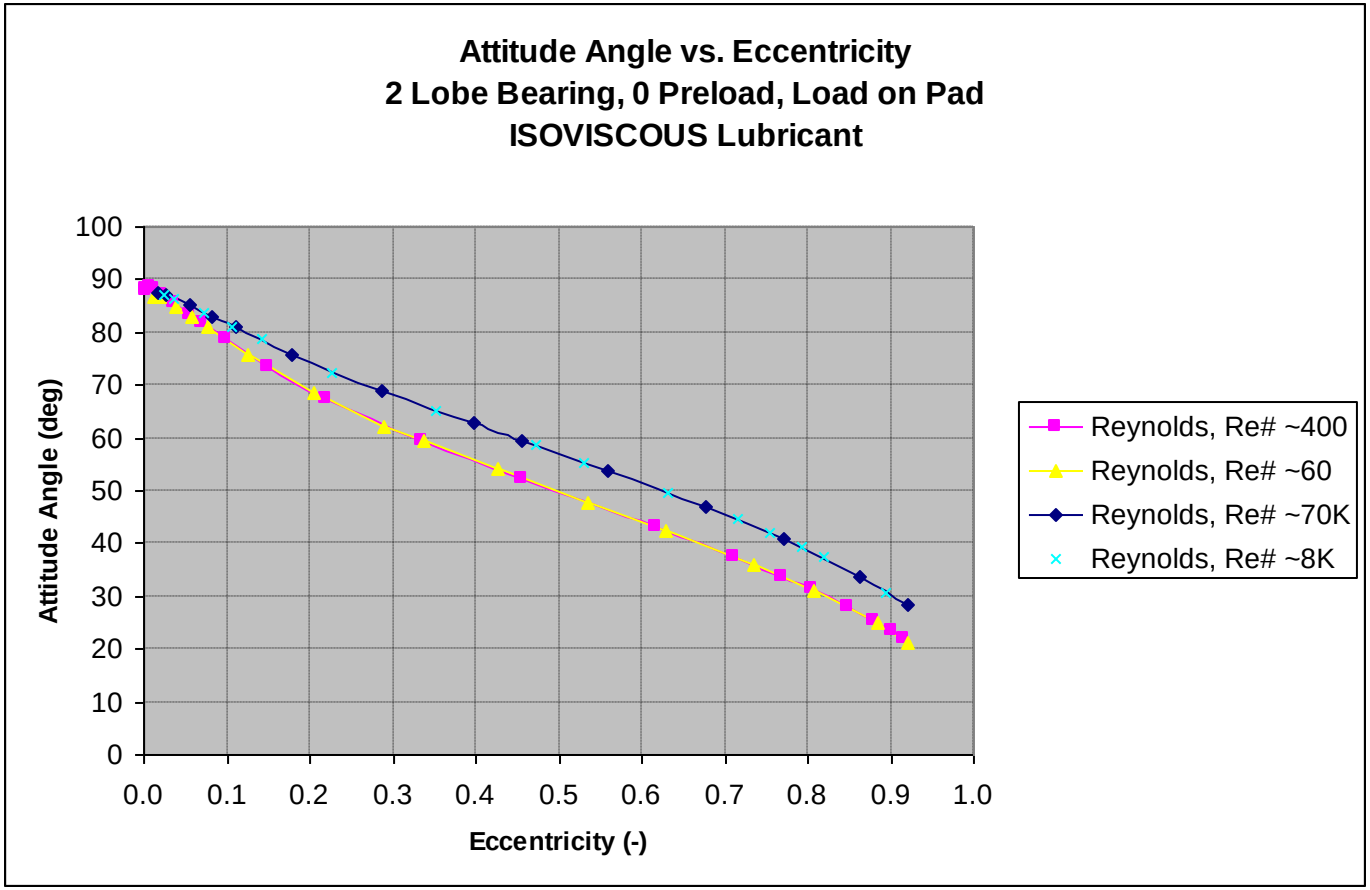
Fully Turbulent Flow Results

- **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)

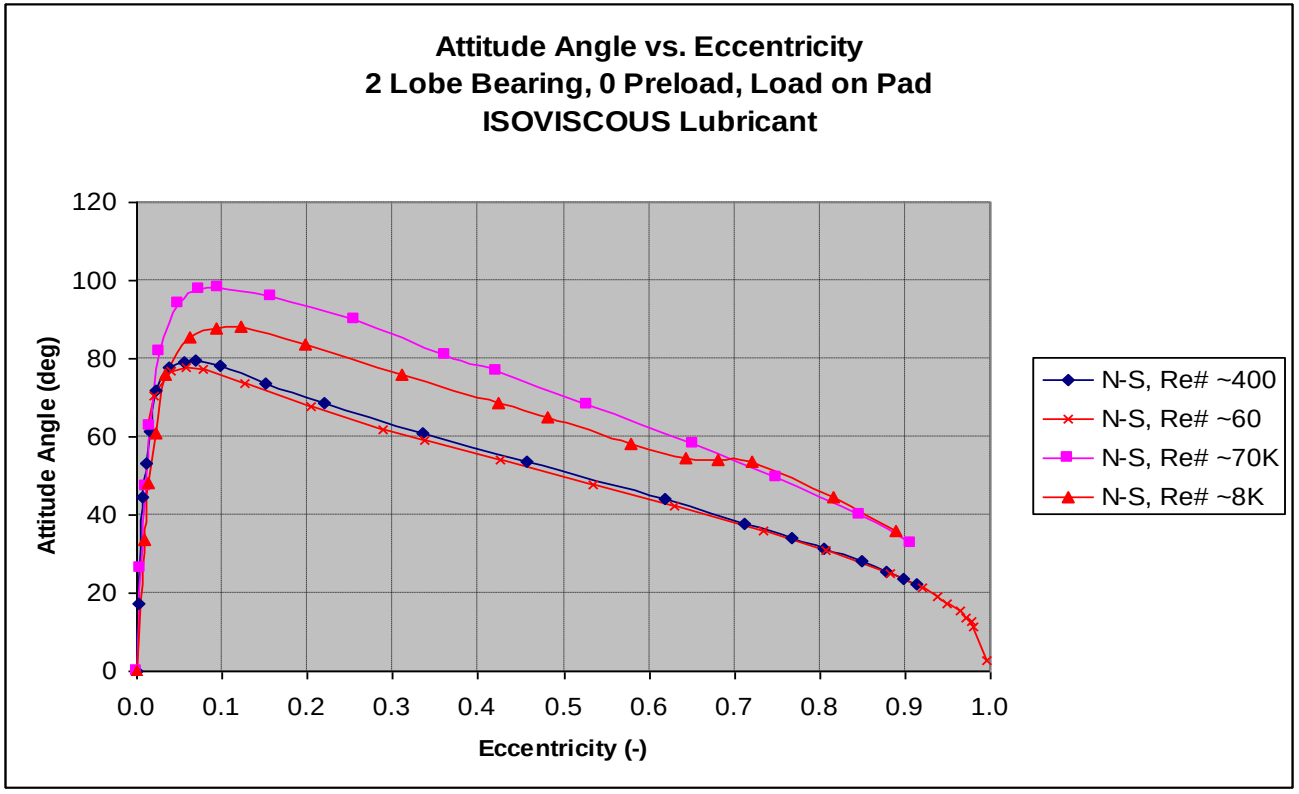
Reynolds Equation Summary



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# ~ 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



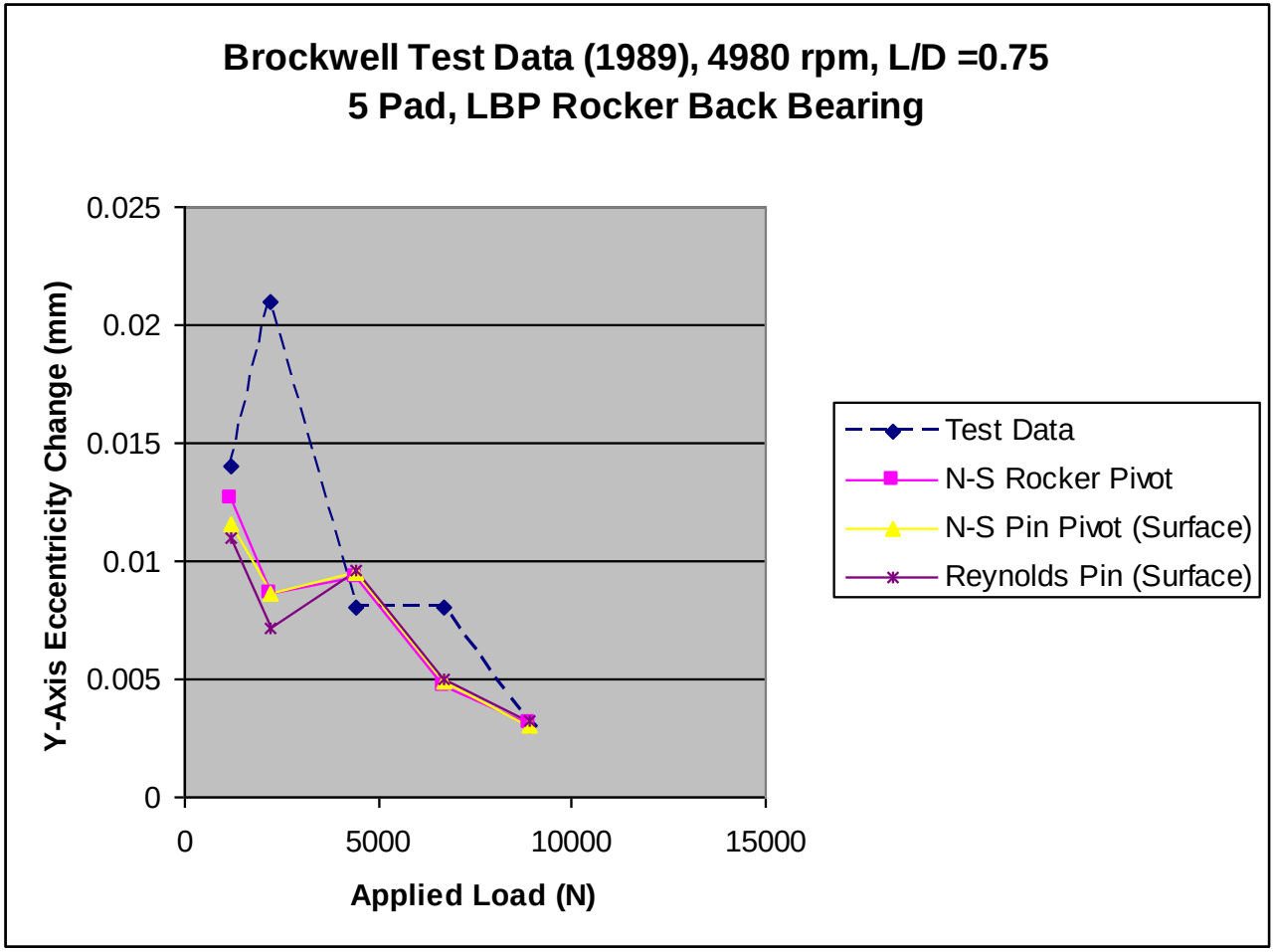
Summary

- **Reynolds Equation Based Bearing Analysis Only Agrees with N-S Based Analysis Under Certain Circumstances**
  - **Low Rotational Speeds (< ~10000 rpm) AND**
  - **Low Reynolds Numbers (< ~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

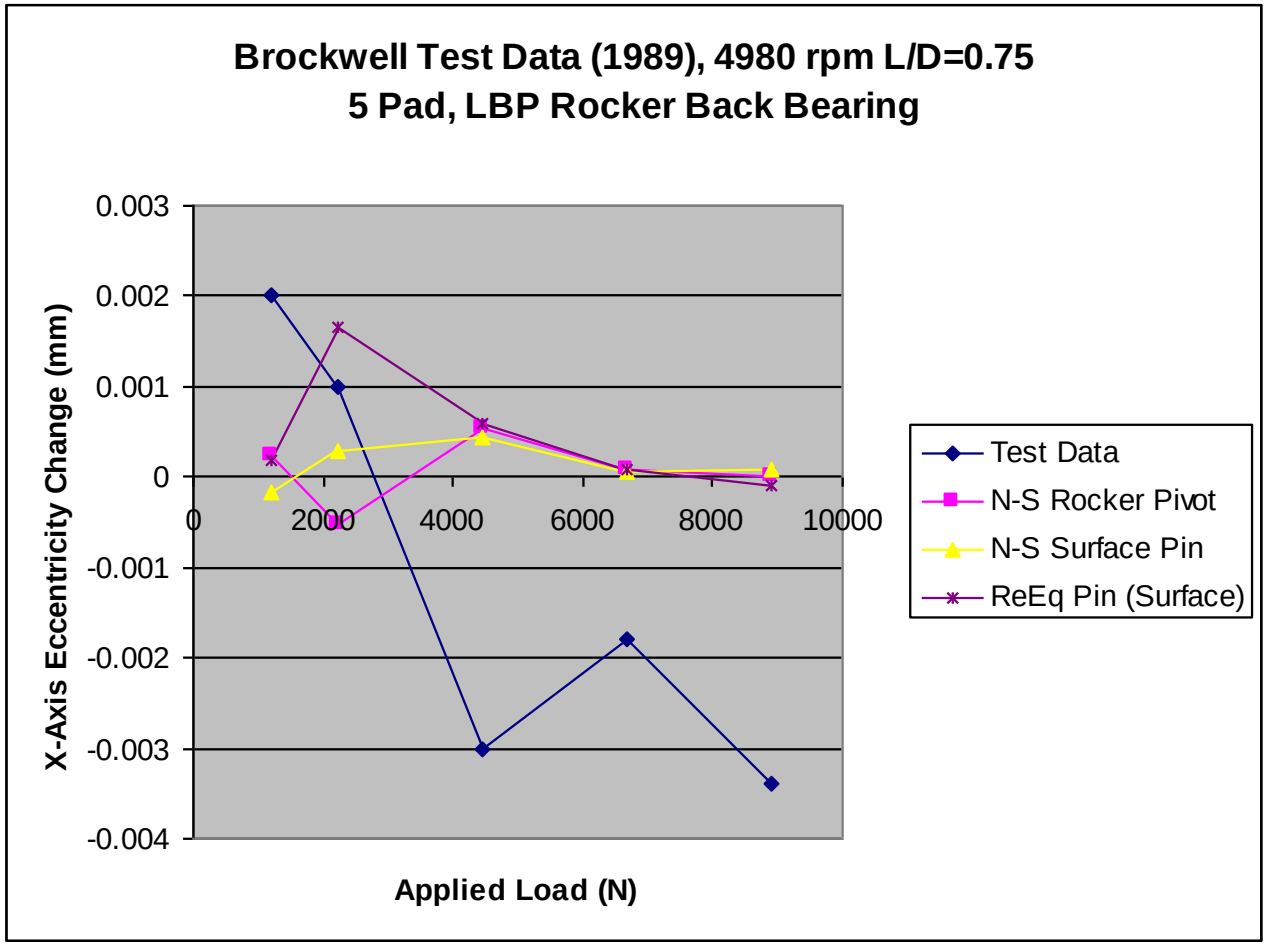
- **Utilizes the Same N-S Stokes Film Solver as Fixed Geometry Bearings**
  - **Additional Iteration Loop Employed to Solve Pad Positions**
- **Pivot Models**
  - **Most Codes Assume Pads Rotate About a Point on the Load Bearing Surface**
  - **RSR has Implemented Advanced Pivot Models to More Accurately 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

Tilting Pad Test Data Comparison



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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%)**