# ADORE

## Advanced Dynamics Of Rolling Elements

# Technical Development

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# Seminar Outline

- Day 1 – Fundamentals and ADORE overview
- Day 2 – ADORE input/output and user instructions
- Day 3 – Dynamics Concepts & Interaction Models I
- Day 4 – Interaction Models II and Other Codes
- Day 5 – Design Procedures and Examples

# ADORE Technical Development

## Day 1: Fundamentals and ADORE Overview

- Workshop objectives
- Modeling fundamentals
- Types of rolling bearing models
    - Short Break
- Stages of development & evolution of ADORE
- ADORE overview and base structure
- Capabilities for performance modeling and diagnostics
    - Lunch Break
- Fundamental modeling approach
- Six-degrees-of-freedom and coordinate transformation
- Basic equations of motion
    - Short Break
- ADORE foundation – Interaction model (what is it?)
- Interaction models in ADORE
- Generic interaction model
- Discussion

# ADORE Technical Development

## Day 2: ADORE Input/Output & User Instructions

- ADORE Data Files
- ADORE Input – Program Input and Control
  - Short Break
- ADORE Input – Bearing Geometry
- ADORE Input – Material Properties
- ADORE Input - Operating Conditions
- ADORE Input – Frictional Interactions
  - Lunch Break
- ADORE Print Output
- ADORE Plot Output
  - Short Break
- Graphic Animation - AGORE

# ADORE Technical Development

## Day 3: Dynamics Concepts & Interaction Models I

- ADORE base formulation
- Fundamentals in dynamic modeling
- Dimensional organization
- Numerical considerations
  - Short break
- Adore code structure
- Interaction modeling recap
- Rolling element to race interaction – normal load
- ADORE module ADRC1
  - Lunch Break
- Frictional interactions basics
- Rolling element to race interaction – frictional loads
- ADORE module ADRD1
  - Short Break
- Significance of frictional Interactions in rolling bearing
- Discussion

# ADORE Technical Development

## Day 4: Interaction Models II and Other Codes

- Cage pocket interactions
- Handling of rolling element collisions
- Hydrodynamics in cage pockets
- ADORE module ADRE1
    - Short break
- Cage/Race interaction
- Hydrodynamics at cage lands
- ADORE module ADRE2
    - Lunch Break
- Life modeling
- ADORE module ADRF1
- Churning & drag effects
- ADORE module ADRF2
    - Short Break
- Customized modeling examples
- ADORE user code module ADRX1
- Other ADORE code modules ADRB, ADRG and ADRH
- Discussion

# ADORE Development

## Day 5: Design Procedures and Examples

- Bearing design procedures
- Stability diagnosis
- Examples
  - Short Break
- Seminar recap
- User examples – direct experience with ADORE
  - Lunch Break
- User Examples continued
- General Discussion

# ADORE Technical Development

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# ADORE Technical Development
## Workshop Objectives

- Basics of modeling of mechanical components
  - Introduction to ADORE
  - Analytical formulation
  - Solution approach
  - ADORE structure
  - Effective use of the code
- Adequate insight for future development and further advancement of ADORE

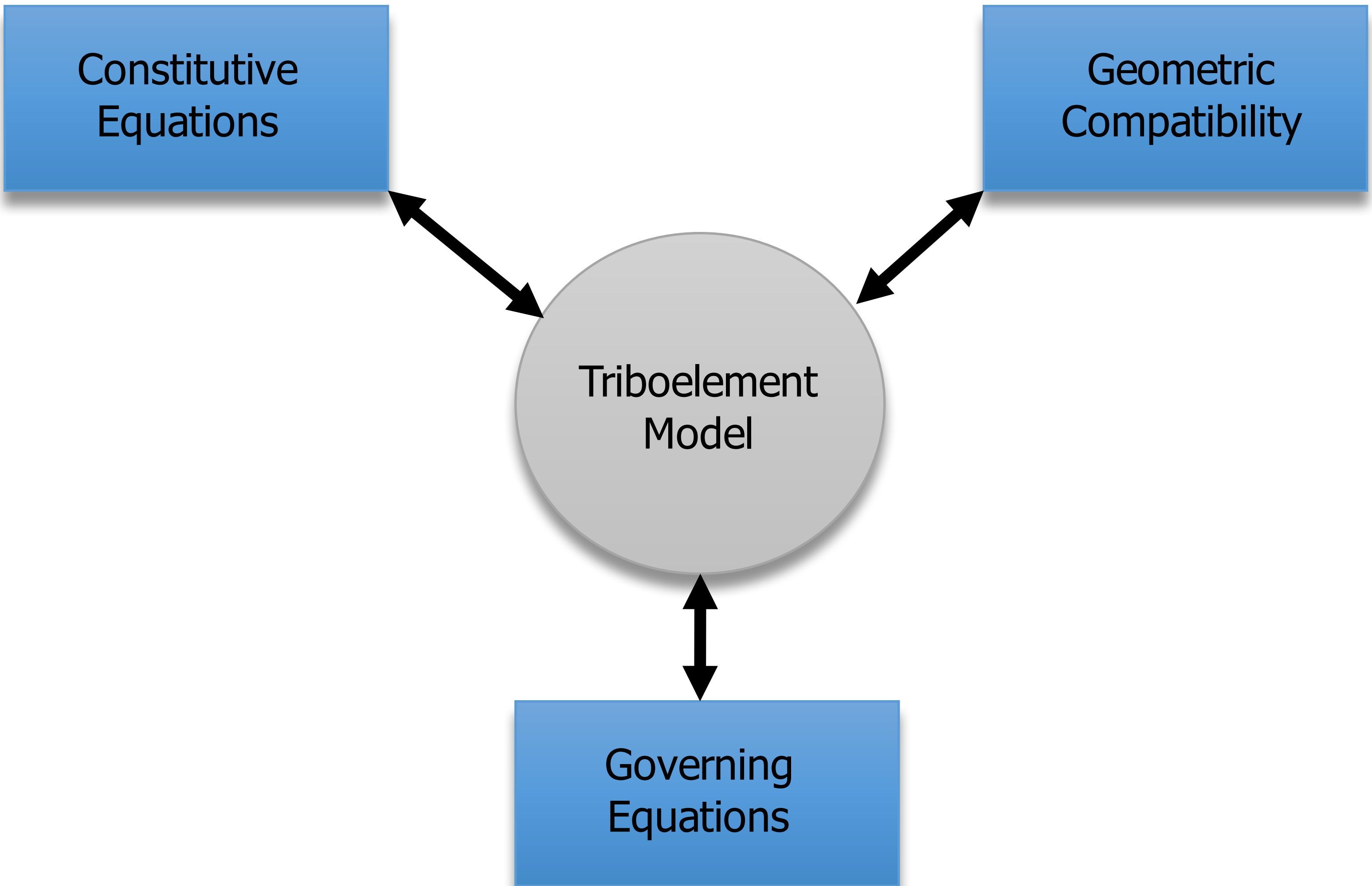
# ADORE Technical Development

## Modeling Fundaments

- Components of a Triboelement Model
- Model Types
- The Model Development Process

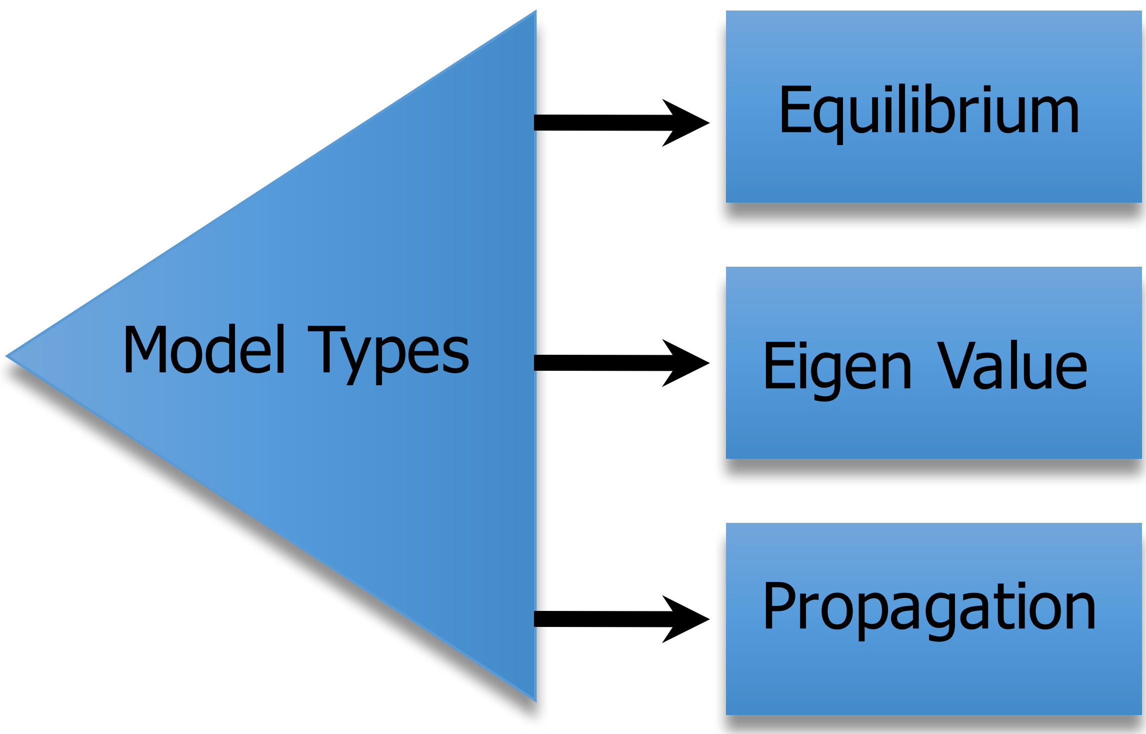
# Triboelement Model

## Model Components



# Triboelement Model

## Model Types




$$\sum F = 0$$

$$\sum G = 0$$

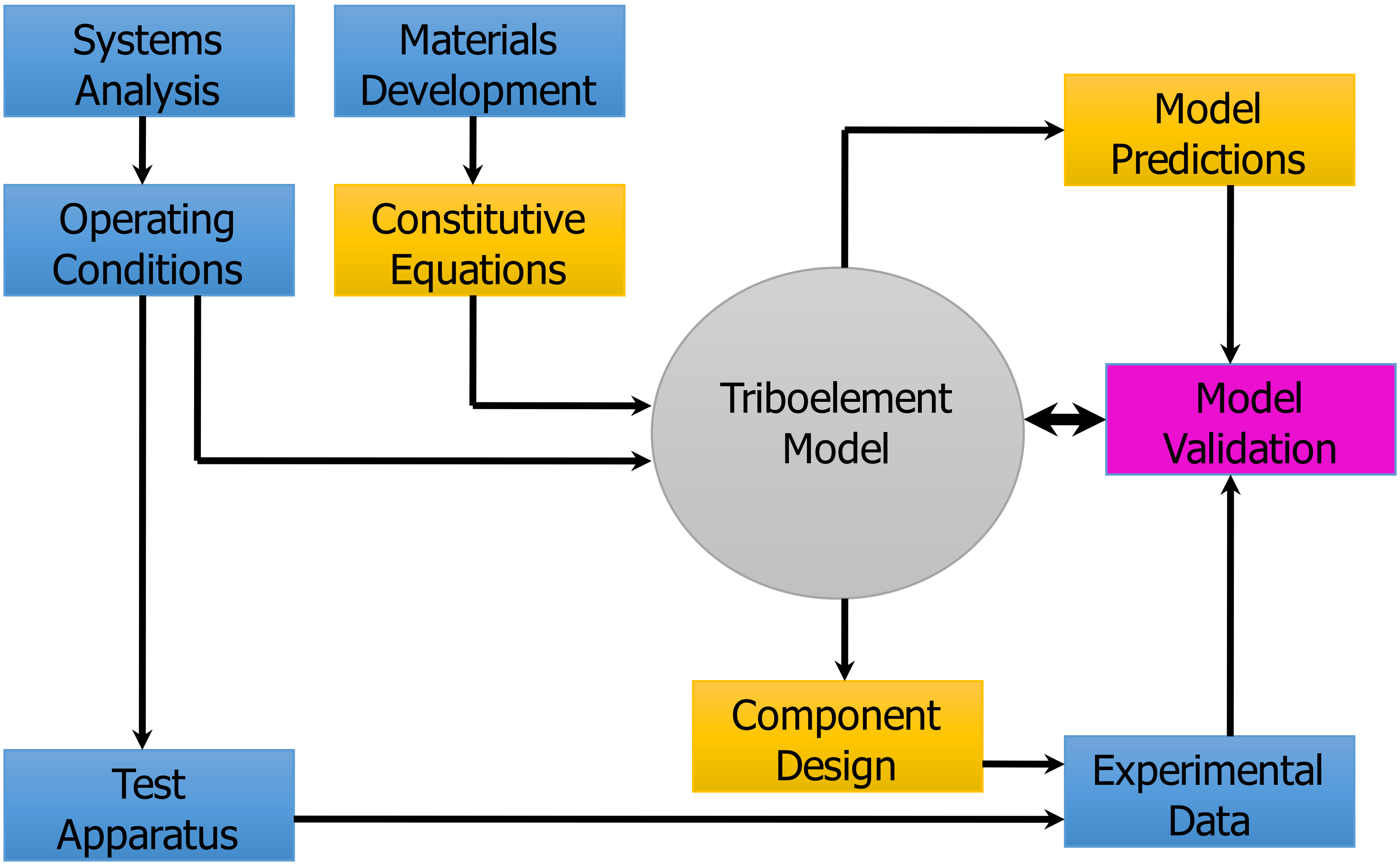
$$AX = \lambda BX$$

$$\sum F = m\ddot{x}$$

$$\sum G = I\dot{\omega}$$

# Triboelement Model

## Model Development Process



# Rolling Bearing Models
## Model Types

- Quasi-Static or Quasi-Dynamic models

$$\sum F = 0$$

$$\sum G = 0$$

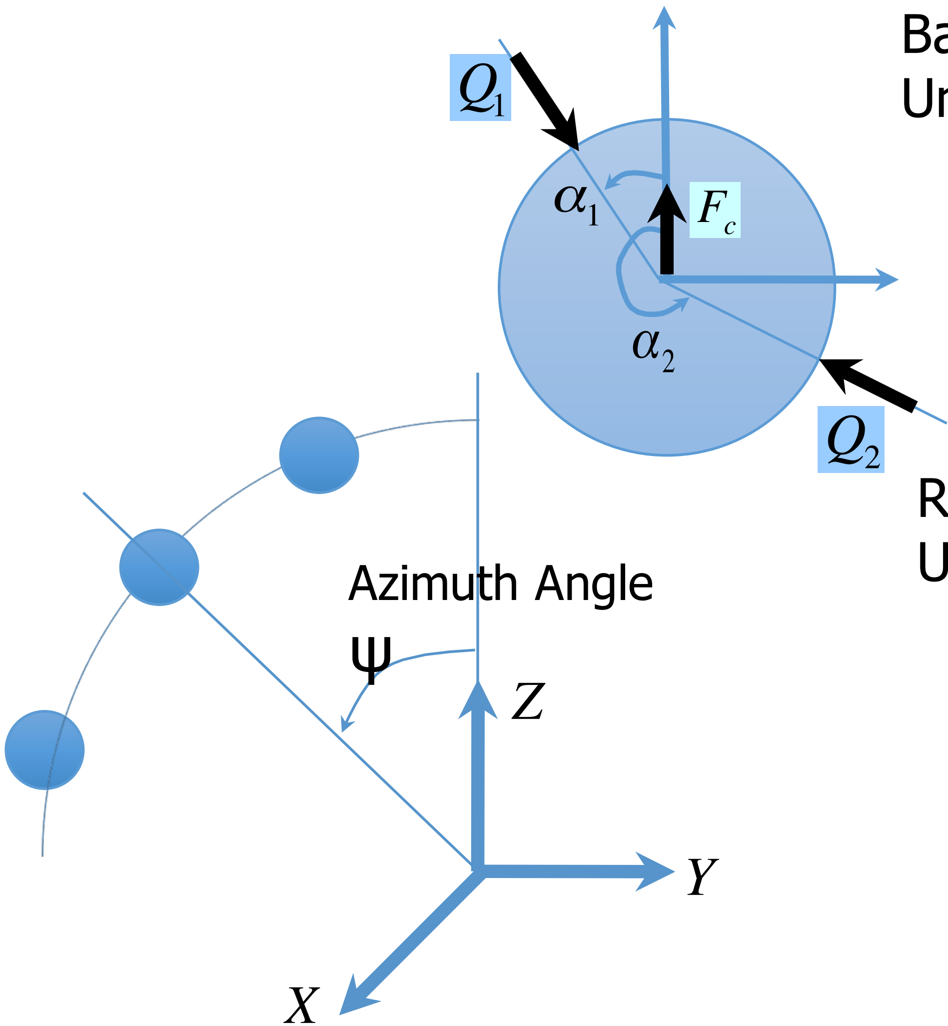
- Time Transient or Dynamic models

$$\sum F = m\ddot{x}$$

$$\sum G = I\dot{\omega}$$

# Rolling Bearing Models

## Static Models: Force Equilibrium in Ball Bearings




Ball Equilibrium:

Unknowns: $x, r$

$$\sum_{j=1}^{2} Q_j \sin\alpha_j = 0$$

$$\sum_{j=1}^{2} Q_j \cos\alpha_j - F_c = 0$$

Race Equilibrium:

Unknowns: $X, Y, Z$

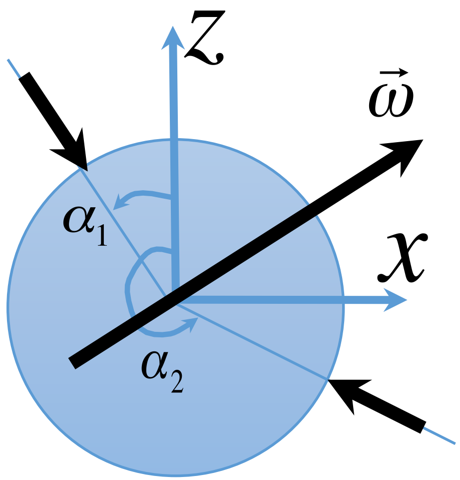
$$\sum_{i=1}^{n} Q_{2i} \sin\alpha_{2_i} = Q_x$$

$$\sum_{i=1}^{n} Q_{2_i} \cos\alpha_{2_i} \sin\psi_i = Q_Y$$

$$\sum_{i=1}^{n} Q_{2_i} \cos\alpha_{2_i} \cos\psi_i = Q_z$$

# Rolling Bearing Models

## Static Models: Ball Angular Velocities




**Unknowns:**

- Angular Velocity Component x
- Angular Velocity Component z
- Orbital Angular Velocity

**Available Equations:**

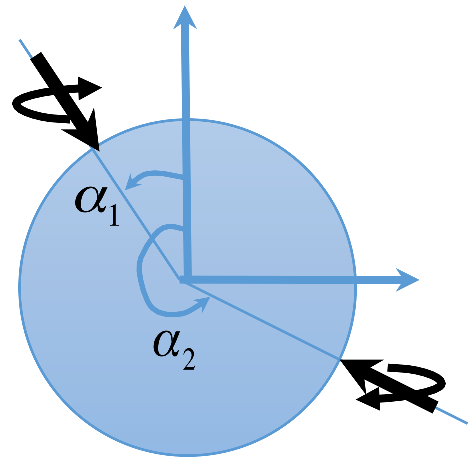
- Pure rolling at one or more points in outer race contact
- Pure rolling at one or more points in inner race contact

**Third Equation?**

- Arbitrary angle – generally used in roller bearing
- Race Control – based on friction torques in race contacts
- Minimize energy in race contacts – new in ADORE

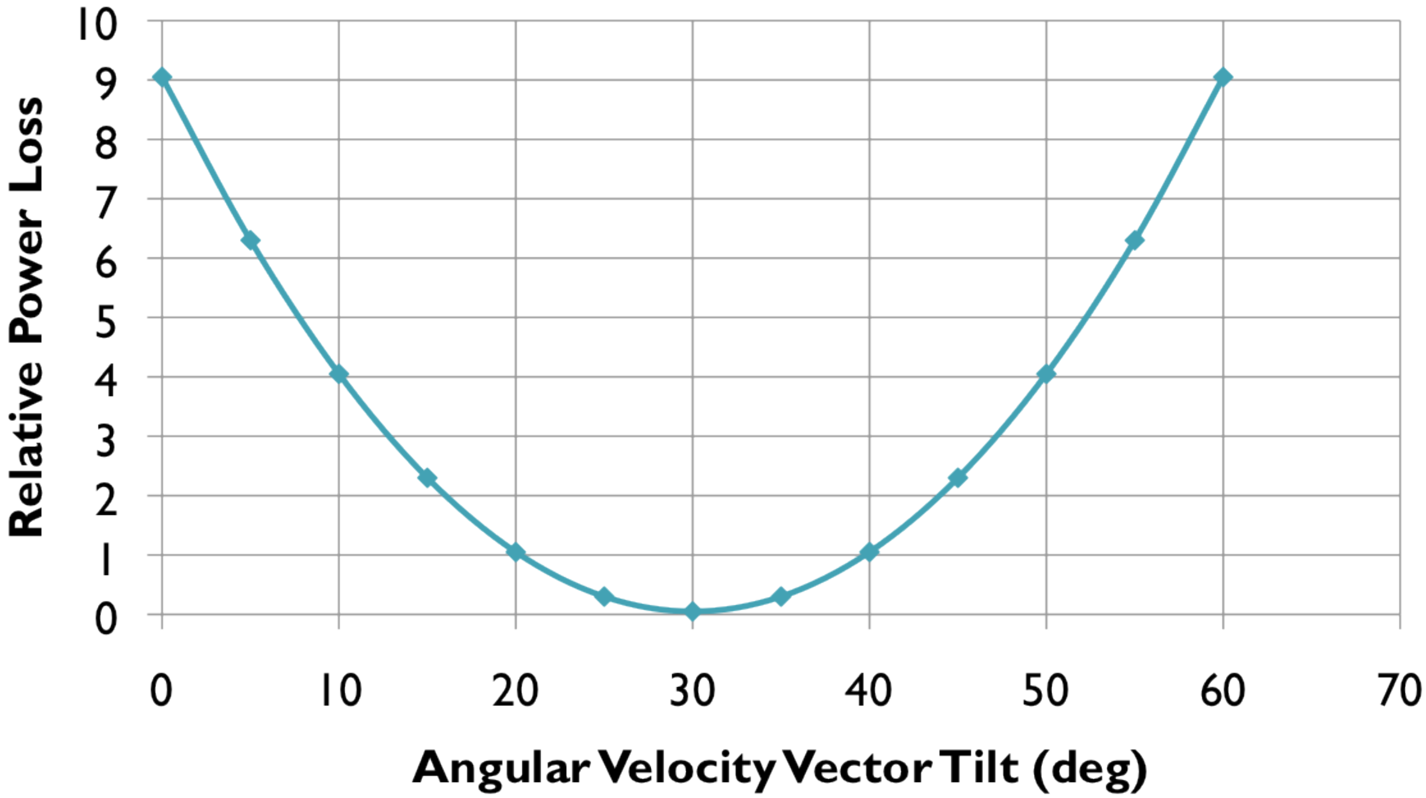
# Rolling Bearing Models

## Race Control Hypothesis for Ball Bearings



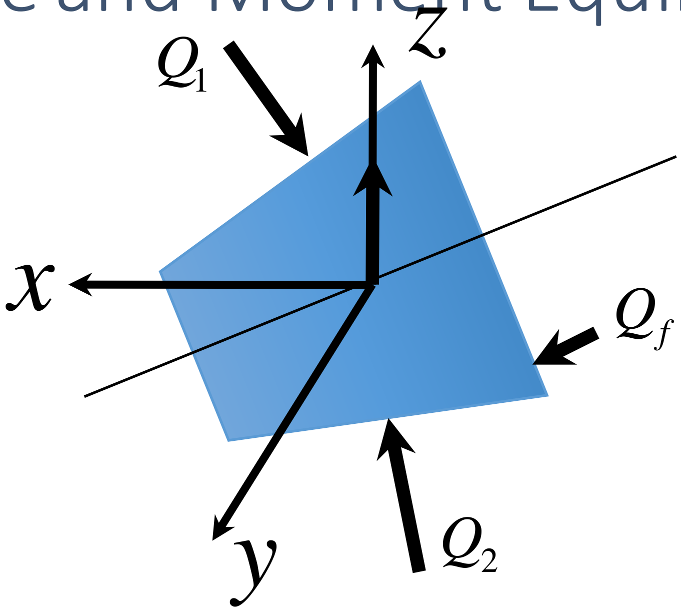

- Compute spin torque with constant friction coefficient on both outer and inner race contacts
- Ball spins only on the contact with smaller spin torque – pure rolling occurs on the other race – controlling race

# Rolling Bearing Models
## Minimum Energy Constraint



# Rolling Bearing Models

## Force and Moment Equilibrium in Roller Bearings




**Unknowns:**

Axial Position: $x$

Radial Position: $z$

Misalignment about y axis: $\theta$

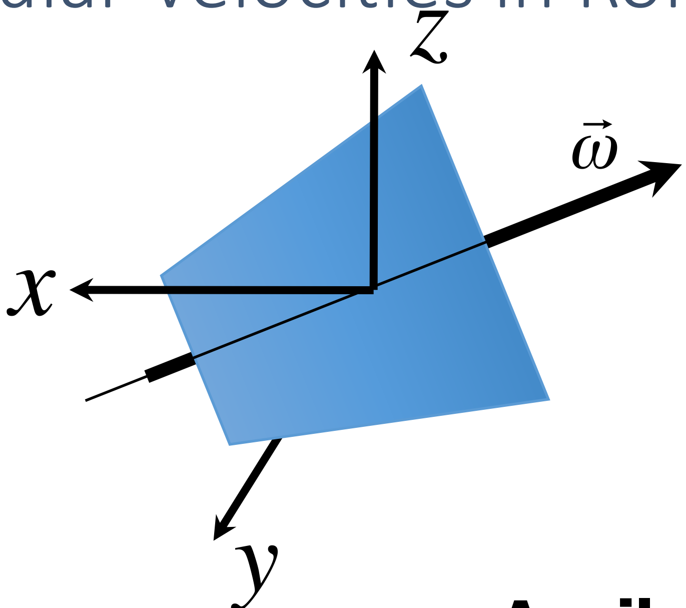
Axial Equilibrium: $$Q_1 \sin\alpha_1 + Q_2 \sin\alpha_2 + Q_f e_x = 0$$

Radial Equilibrium: $$Q_1 \cos\alpha_1 + Q_2 \cos\alpha_2 - F_c + Q_f e_r = 0$$

Moment Equilibrium: $$M_{y_1} + M_{y_2} + M_{y_f} + G_y = 0$$

# Rolling Bearing Models

## Angular Velocities in Roller Bearings




**Roller turns about its own axis**

Unknowns:

Angular Velocity

Oribital Velocity

**Available equations**

Pure rolling on outer race

Pure rolling on inner race

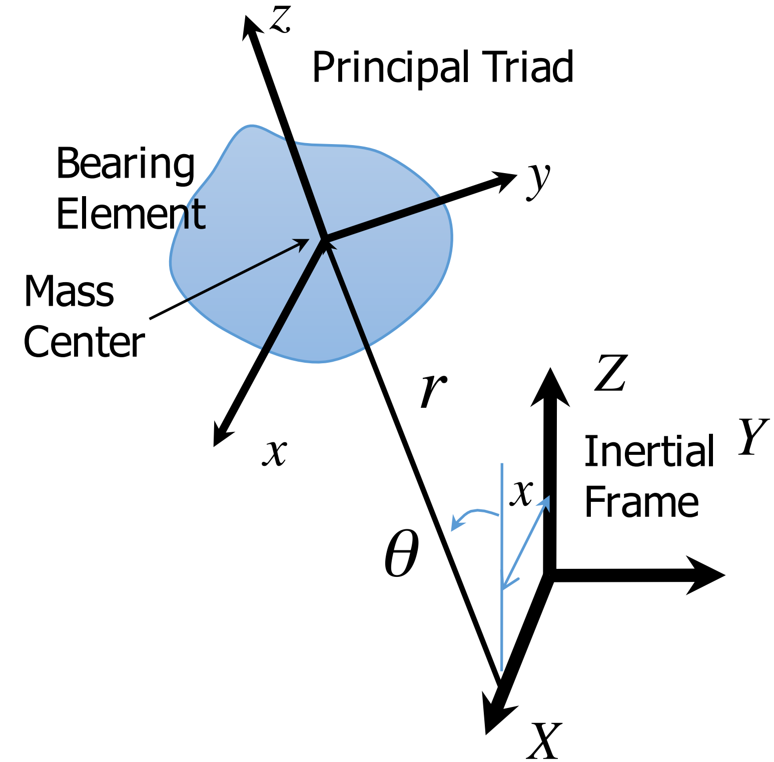
# Rolling Bearing Models
## Dynamic Model

- Mass Center Motion

$$m\ddot{x} = F_x \qquad m\ddot{x} = F_x$$

$$m\ddot{y} = F_y \quad \text{or} \quad m\ddot{r} - mr\dot{\theta}^2 = F_r$$

$$m\ddot{z} = F_z \qquad mr\ddot{\theta} + 2m\dot{r}\dot{\theta} = F_\theta$$




- Angular Motion

$$I_1\dot{\omega}_1 - (I_2 - I_3)\omega_2\omega_3 = G_1$$

$$I_2\dot{\omega}_2 - (I_3 - I_1)\omega_3\omega_1 = G_2$$

$$I_3\dot{\omega}_3 - (I_1 - I_2)\omega_1\omega_2 = G_3$$

Classical Euler Equations

# Rolling Bearing Models
## Model Differences

| Static | Dynamic |
|---|---|
| Algebraic equations of equilibrium | Differential equations of motion |
| Race control / kinematic hypothesis | No such constraint |
| All velocities are constant | Arbitrary accelerations |
| Fixed interactions | Interactions vary with time |
| Restricted treatment of skid & skew | Real time simulation of all motions |
| No treatment of cage instability | Real time simulation of cage motion |
| Fixed applied loads | Load may vary with time |
| Convergence problems with EHD | No such numerical problems |
| One solutions contains all parameters | Time transient solutions |

# Rolling Bearing Models

## Practical Significance of the Two Types of Models

- Static Model
  - Overall load distribution
  - Contact stress
  - Nominal film thickness
  - Fatigue life
  - Bearing stiffness
- Dynamic Model
  - Cage instability
  - Rolling element skid
  - Roller skew
  - Lubrication effects
  - Wear Modeling
  - Heat generation
  - Bearing torques
  - Dynamic loads
  - Irregular geometry
  - Optimization of manufacturing tolerances
  - Bearing noise

# ADORE Technical Development

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# Rolling Bearing Models
## Development Stages

| Static Models | Time | Dynamic Models |
|---|---|---|
| Jones - Harris | 1960's | |
| | 1970 | BASDAP – Walters & Kannel |
| | 1973 | BDYN - Gupta |
| SHABERTH<br>Crecelius & Pirvics | 1976 | |
| | 1977 | DREB - Gupta |
| TRANSIM - Ragen | 1979 | TRIBO1 – Brown et al |
| CYBEAN – Kleckner et al | 1980 | |

# Rolling Bearing Models
## Stages of Development

| Quasi-Static Models | Time | Dynamic Models |
|---|---|---|
| | 1981 | Conry<br>RAPIDREB - Gupta |
| SPHERBEAN<br>Kleckner & Pirvics | 1982 | |
| | 1983 | ADORE - Gupta |
| | 1984 | SEPDYN - Meeks |
| | 1985 | ADORE/PC - Gupta |
| PREBES - Sague | 1987 | |
| COBRA - Poplawski | 1989 | |

# Rolling Bearing Models
## Stages of Development

| Quasi-Static Models | Time | Dynamic Models |
|---|---|---|
| | 1994 | AGORE - Gupta |
| | | BASDREL, BABERDYN - Meeks |
| | 1999 | BEAST –<br>Stacke, Fritzson & Nordling |
| | 2010 | CAGEDYN - Houpert |
| | | |

2011, STLE Tribology Transactions, 54, 394-403, Gupta, P. K., "Current Status of and Future Innovations in Rolling Bearing Modeling".

# ADORE Overview

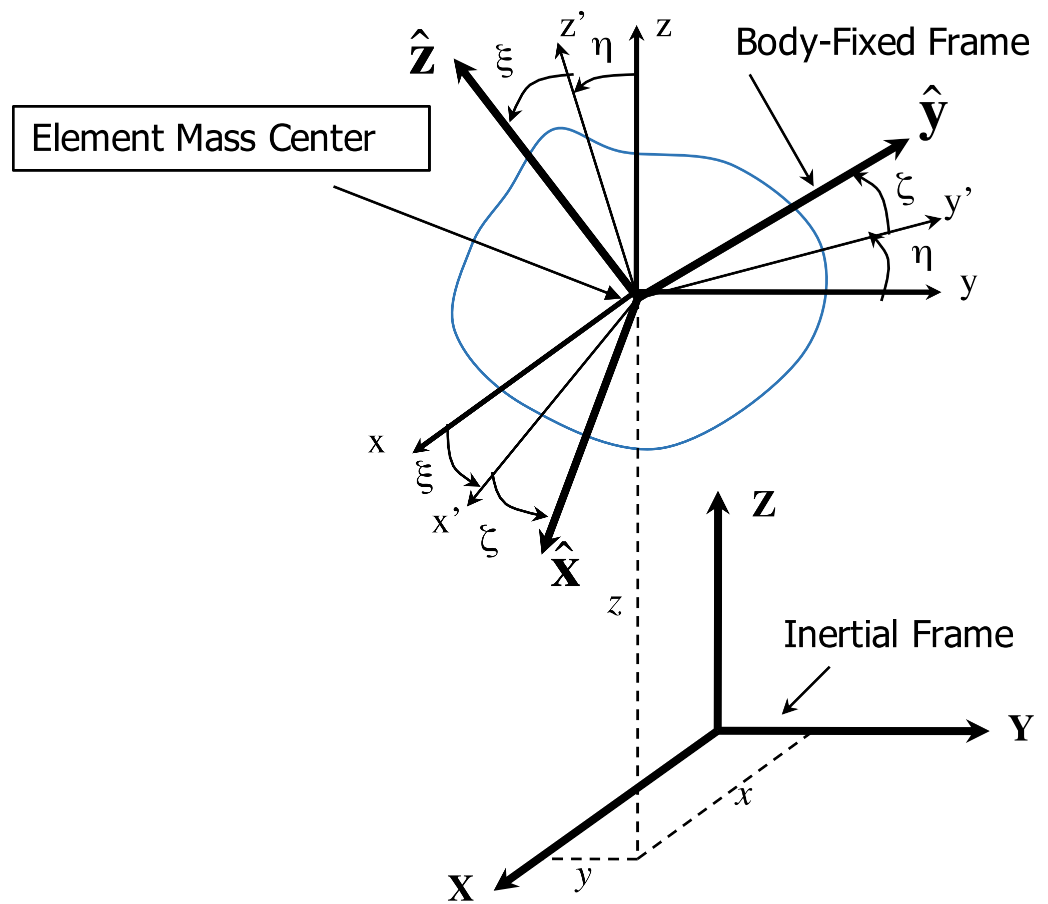
- Both types of models
  - Quasi-static
  - Real-time dynamic
- Primary purpose of quasi-static model
  - Estimation of initial conditions for dynamic simulation
- Eigen value modeling
  - Control on time step
  - Real-time bearing element acceleration
  - Post processing – Fast Fourier transform

# ADORE Overview

- Generalized dynamics model
- Complete six-degrees-of-freedom system
- Real-time simulation of bearing performance
- Highly modular structure

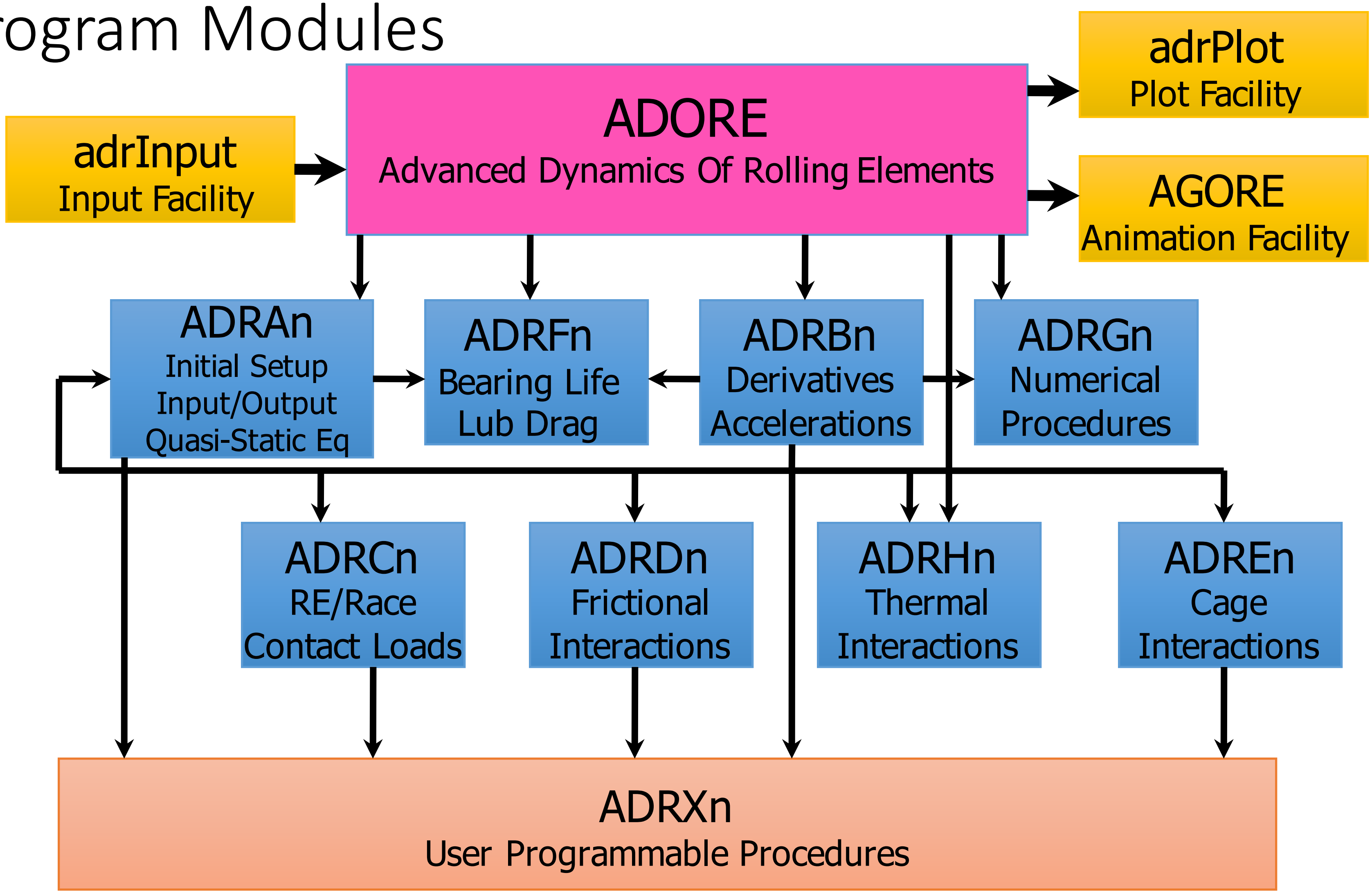
# ADORE Overview

## Generalized Six-Degrees-of-Freedom

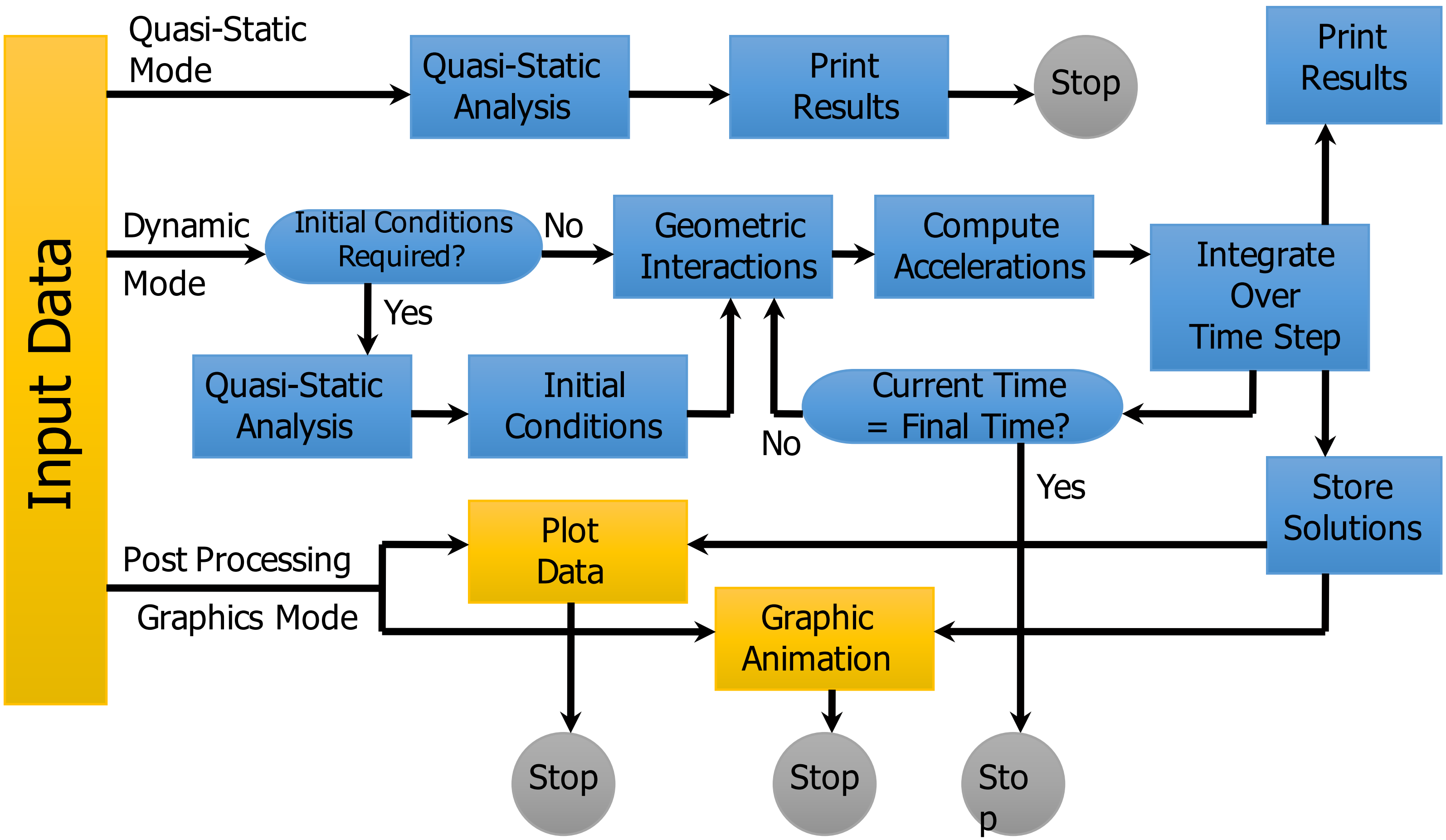


# ADORE Overview

## Program Modules



# ADORE Overview
## Simplified Flow Chart



# ADORE Overview
## Model Capabilities

- Bearing types - ball, cylindrical, taper and spherical taper roller
- Geometrical imperfections
- Time-varying operating conditions
- Lubricant modeling
- External constraints
- Centrifugal and thermal distortion
- Bearing power loss
- Thermal interactions
- Cage stability
- Roller skew
- Rolling element skid
- Wear modeling
- Bearing noise
- Rotating reference frames
- Stiffness and fatigue life

# ADORE Overview
## User Interfaces

- Data input facility - AdrInput
  - Java based interactive code
  - Output – ADORE Input file
- Plot output facility - AdrPlot
  - Java based facility
  - Input – Computed solutions from ADORE
  - Output - Interactive display of all solutions
- Animation facility – AGORE
  - Java based code
  - Input – Dynamics solutions from ADORE
  - Output – Animated display of bearing motion

# ADORE Overview
## Code Architecture

- FORTRAN Code
  - Full conformance to FORTRAN 90/95 standard
  - Top down design
  - No statement labels and “GO-TO” statements
  - Extensive documentation
- Distribution
  - All source codes
  - Related compilers required
  - No license codes
  - Periodic program updates
- Future considerations
  - Porting to C/C++ and/or Java
  - Primary limitations – Scientific computations
  - Multi-dimensional arrays
  - Floating point processing speeds
  - Complex numbers

# ADORE Overview
## Development Time Line

| Time Range | ADORE Related Development |
|---|---|
| 1971-75 | Fundamental Development |
| 1976-77 | Fully dynamics model for both ball and roller bearings |
| 1978-82 | Advancements in numerical methods |
| 1982-83 | Geometrical generalizations, tapered and spherical bearings |
| 1984 | First publication of ADORE |
| 1985-86 | Manufacturing tolerances, solid lubrication and wear |
| 1987-1988 | ADORE validation |
| 1989-1990 | Tapered roller bearing enhancements, life modification factors |

# ADORE Overview
## Development Time Line contd..

| Time Range | ADORE Related Development |
|---|---|
| 1990-92 | Traction model advancements |
| 1993-95 | Graphic animation and AGORE |
| 1996-99 | ADORE rewritten in FORTRAN-90 |
| 2000-01 | Java interfaces |
| 2002-03 | Thermal modeling, life modification advancements |
| 2004-05 | Visco-elastic traction models, large time domain simulations |
| 2006-08 | Materials data base, spherical roller bearing enhancements |
| 2009-10 | Predictor-Corrector, ball-to-ball contact, spherical pockets |
| 2010-11 | Numerical enhancements to line-contact modeling |

# ADORE Overview

## Development Time Line contd..

| Time Range | ADORE Related Development |
|---|---|
| 2012-14 | Generalized life model development |
| 2015-…. | Ongoing life and thermal modeling |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

# ADORE Overview

## Capabilities for Performance Modeling and Diagnostics

- Real-time simulation of bearing performance
- Wide range of applications
  - Good correlations with field observations
  - Problem fixes via parametric evaluation
- Certified design tool in critical applications
- Successful simulation of bearings in complex operating environment

# ADORE Overview
## Key Performance Parameters

- Bearing fatigue life
- Stiffness – integration with rotor dynamics
- Heat generation or power loos
- Stability of bearing element motion
- Wear

# ADORE Overview
## Current Distribution

- Major bearing manufacturers around the world
- Gas turbine engine manufactures
- Aero space companies
- Computer companies
- Consulting and R&D companies
- Universities
- US Air Force and Navy
- NASA

# ADORE Overview

## Notable Applications

- Space shuttle turbo pump
- Bearing applications related to space station
- Bearings for high-speed rail-road
- Cage failures under dynamic applied loads
- Unbalance and vibratory load applications
- Rapid accelerations and variable speeds
- Inertial guidance systems
- Communication satellites

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# ADORE Development
## Fundamental Modeling Approach

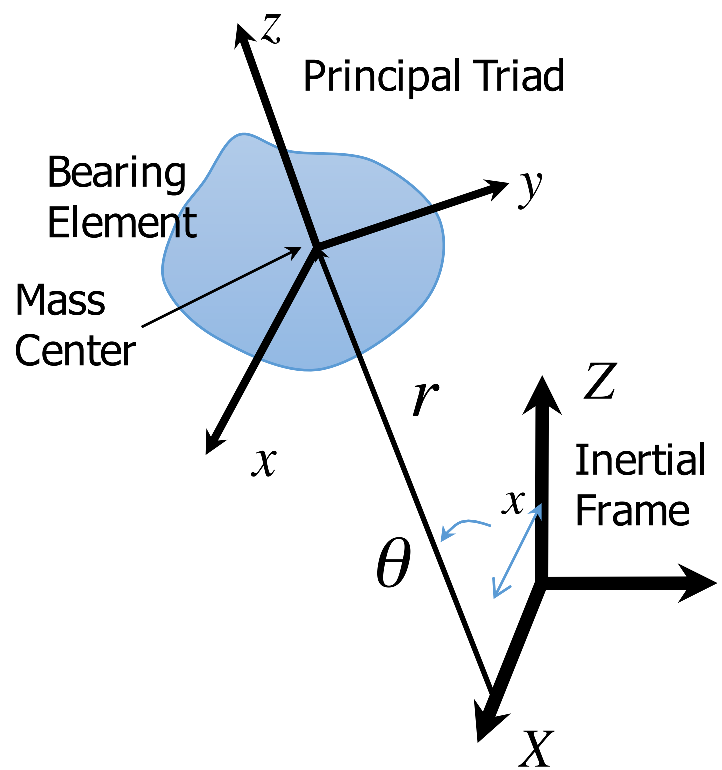
- Track motion on each bearing element in space
- Integrate differential equations of motion

$$m\ddot{x} = \vec{F}$$
$$I\ddot{\theta} = \vec{G}$$

or

$\dot{x} = v$ and $m\dot{v} = \vec{F}$

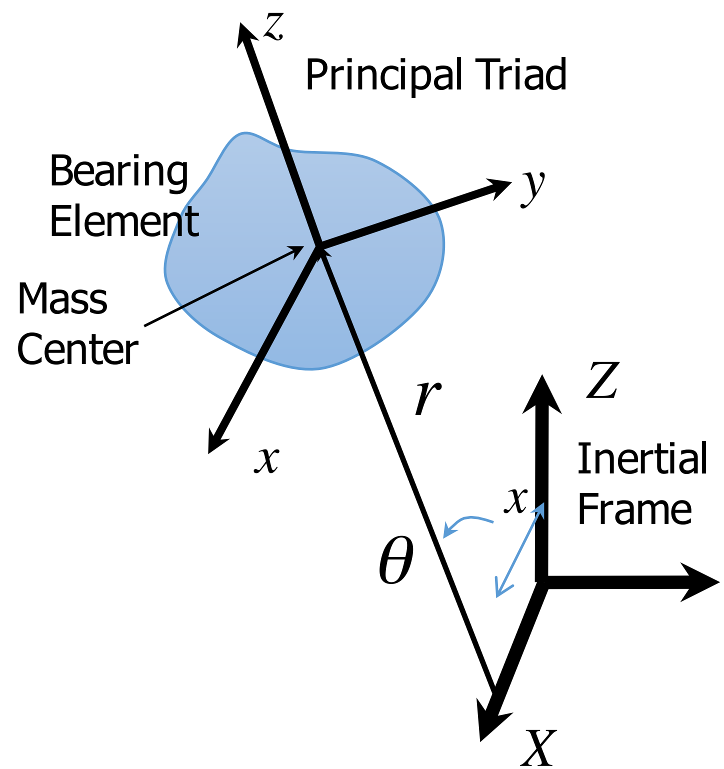
$\dot{\theta} = \omega$ and $I\dot{\omega} = \vec{G}$



# ADORE Development

## Understanding Displacements

- Linear displacements
  - Mass center coordinates
- Angular displacements
  - Angular orientation
- Six-Degrees of Freedom
  - Three linear displacement coordinates
  - Three angles defining angular orientation

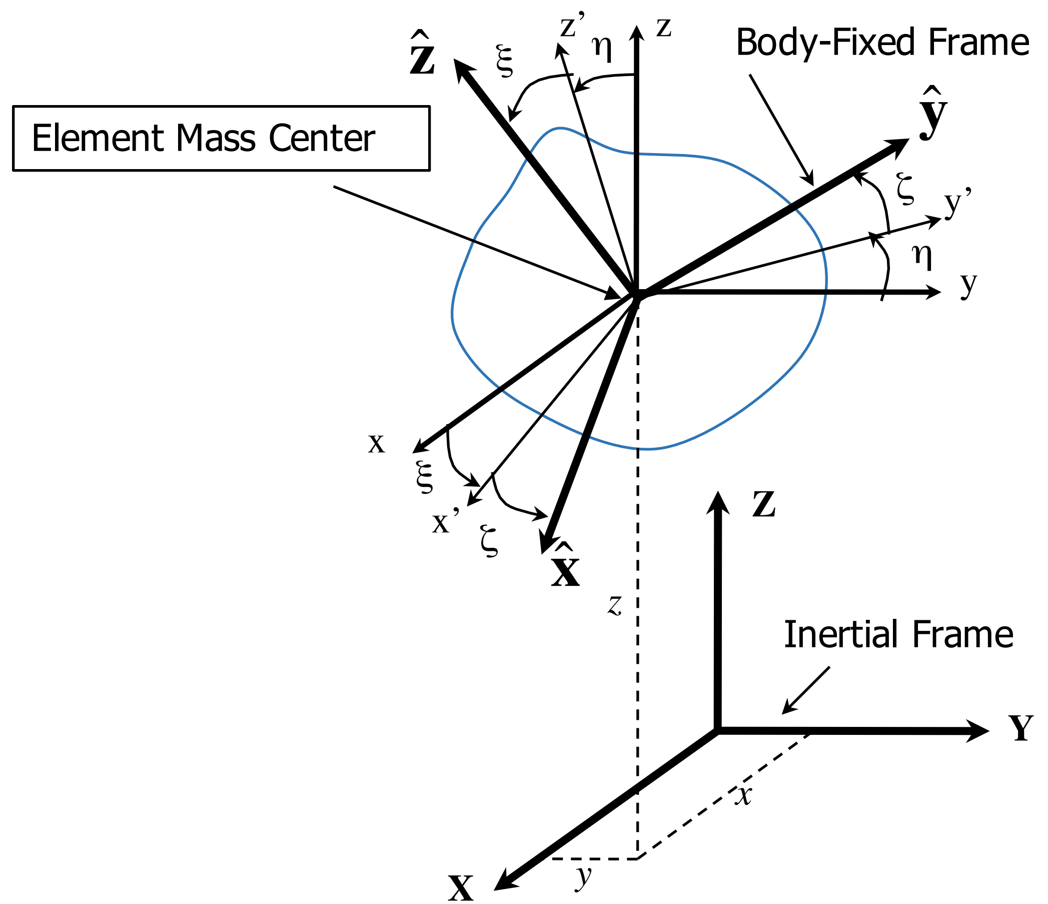


# ADORE Development
## Understanding Force & Moments

- Prescribed Forces
  - Externally imposed forces
  - Internally generated forces
    - Interaction between elements
- Moment
  - Force
  - Position of Force
  - Moment cross product of position and force

$$\vec{G} = \vec{r} \times \vec{F}$$

# ADORE Development
## Six-Degrees of Freedom & Base Coordinates



# ADORE Development

## Coordinates Transformations

$$\mathbf{r}^b = [T_{ib}]\mathbf{r}^b$$

$$T_{ib} = \begin{bmatrix} \cos\xi\cos\zeta & \begin{matrix}\cos\eta\sin\zeta \\ +\sin\eta\sin\xi\cos\zeta\end{matrix} & \begin{matrix}\sin\eta\sin\zeta \\ -\cos\eta\sin\xi\cos\zeta\end{matrix} \\ -\cos\xi\sin\zeta & \begin{matrix}\cos\eta\cos\zeta \\ -\sin\eta\sin\xi\sin\zeta\end{matrix} & \begin{matrix}\sin\eta\cos\zeta \\ +\cos\eta\sin\xi\sin\zeta\end{matrix} \\ \sin\xi & -\sin\eta\cos\xi & \cos\eta\cos\xi \end{bmatrix}$$

Programmed in Adrb2

Orthogonal Matrix

$$T_{ib} = [C_{jk}]$$

$$T_{bi} = T_{ib}^{-1} = [C_{kj}]$$

# ADORE Development

## Angles to Angular Velocities

$$\boldsymbol{\omega}^b = [\mathcal{C}] \begin{Bmatrix} \dot{\eta} \\ \dot{\xi} \\ \dot{\zeta} \end{Bmatrix}$$

$$[\mathcal{C}] = \begin{bmatrix} \cos\xi\cos\zeta & \sin\zeta & 0 \\ -\cos\xi\sin\zeta & \cos\zeta & 0 \\ \sin\xi & 0 & 1 \end{bmatrix}$$

$$[\mathcal{C}]^{-1} = \begin{bmatrix} \dfrac{\cos\zeta}{\cos\xi} & -\dfrac{\sin\zeta}{\cos\xi} & 0 \\ \sin\zeta & \cos\zeta & 0 \\ -\tan\xi\cos\zeta & \tan\xi\sin\zeta & 1 \end{bmatrix}$$

# ADORE Development

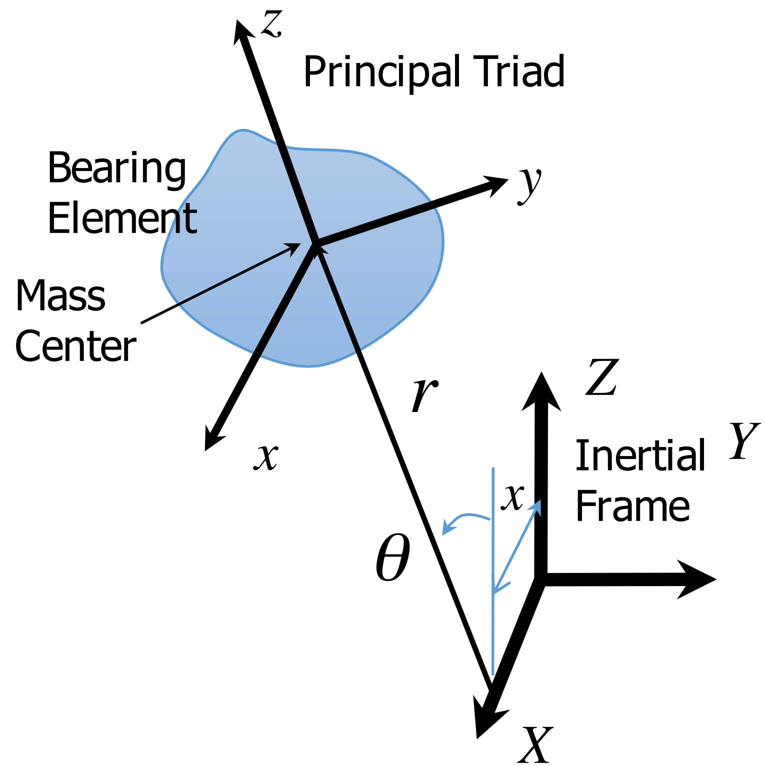
## Basic Equations of Motion

- Mass Center Motion

$$m\ddot{x} = F_x \qquad m\ddot{x} = F_x$$

$$m\ddot{y} = F_y \quad \text{or} \quad m\ddot{r} - mr\dot{\theta}^2 = F_r$$

$$m\ddot{z} = F_z \qquad mr\ddot{\theta} + 2m\dot{r}\dot{\theta} = F_\theta$$




- Angular Motion

$$I_1\dot{\omega}_1 - (I_2 - I_3)\omega_2\omega_3 = G_1$$

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Classical Euler Equations

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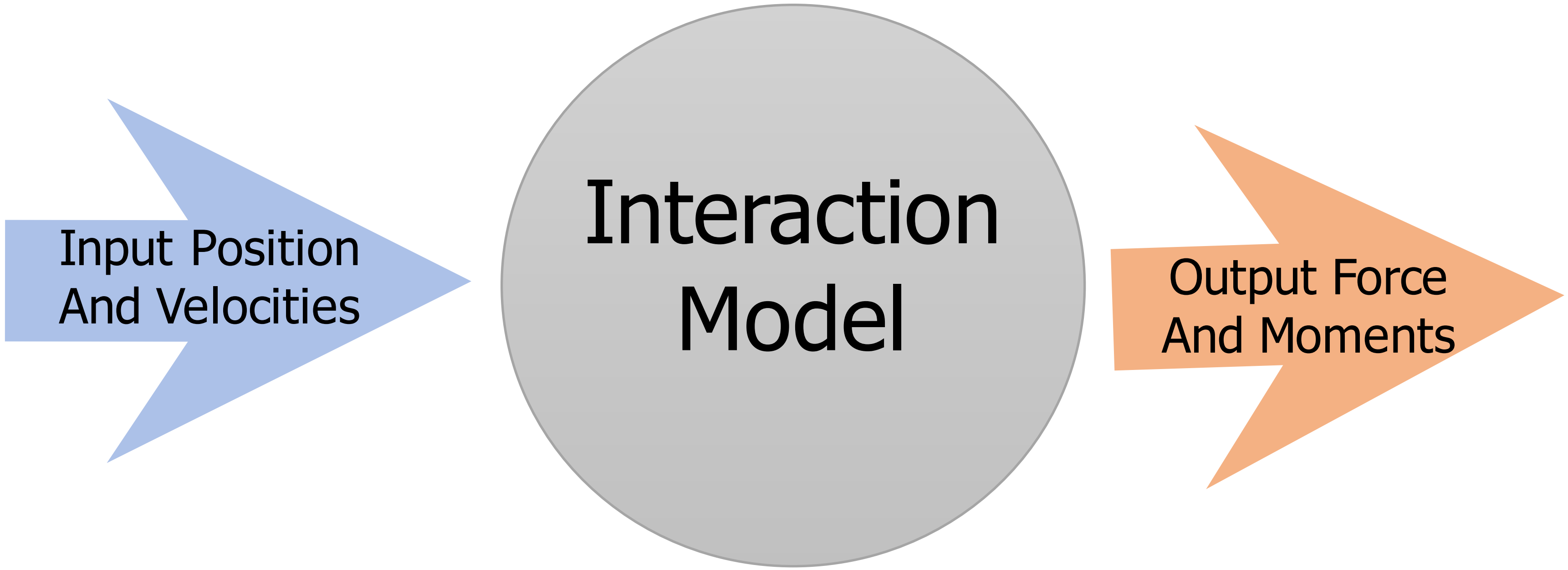
# ADORE Foundation

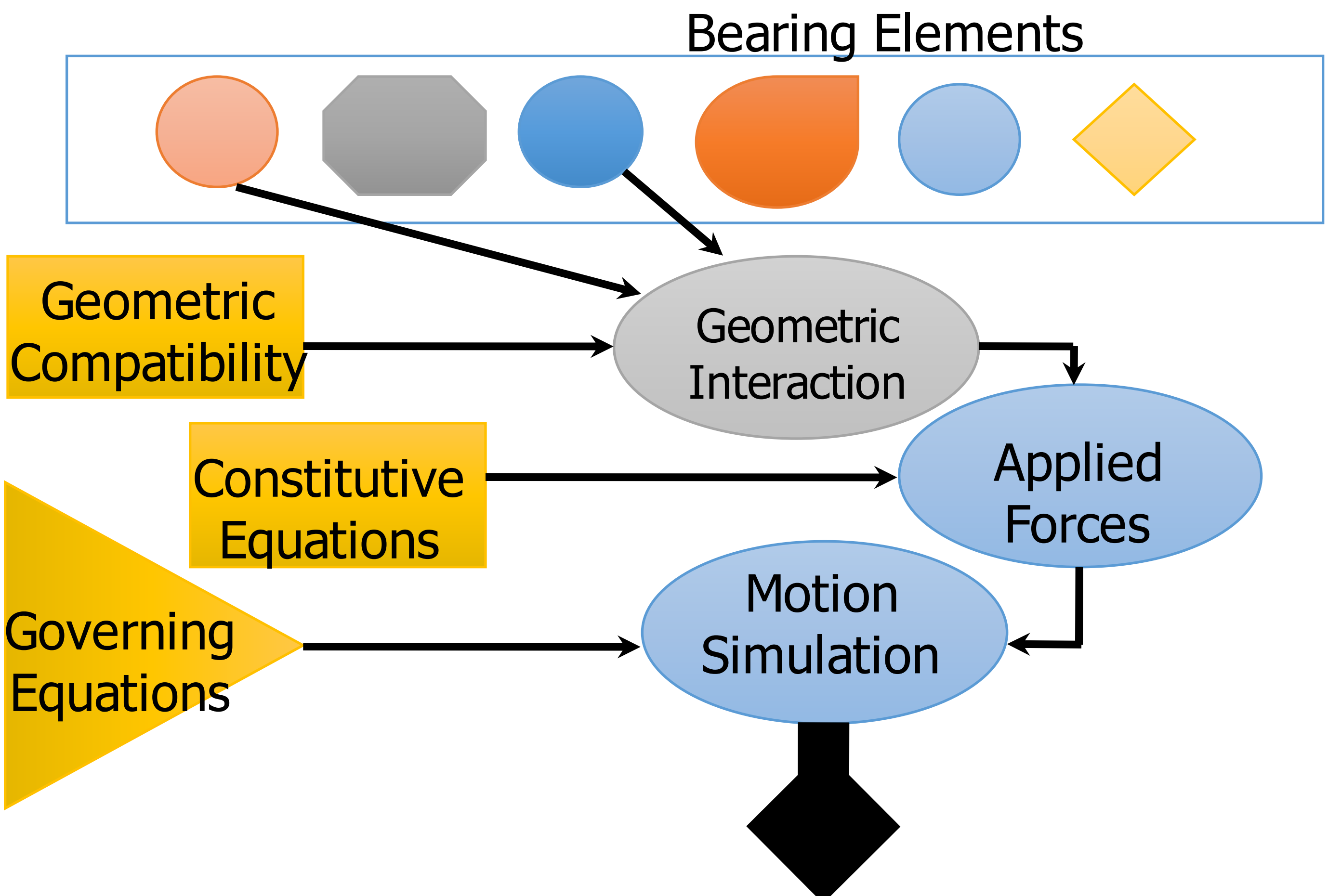
## Base Formulations

- Displacement formulations
- Force formulations
  - Prescribed external
    - May be time dependent
  - Internally generated
    - **Interaction models**

# Interaction Model
## What is it?



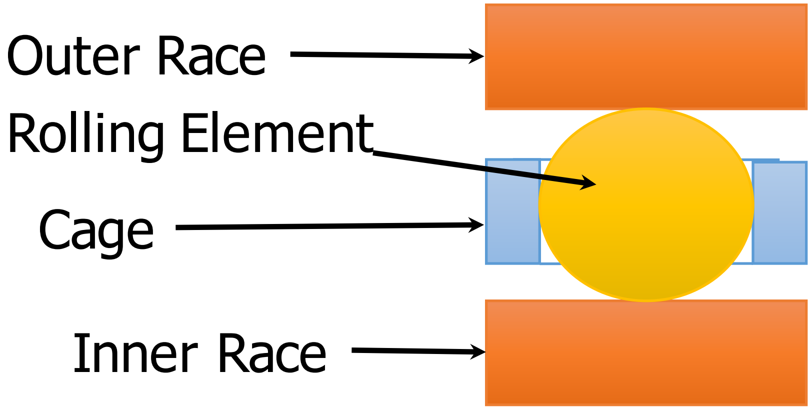
# ADORE Foundation
## Interaction Model Fundamentals



# ADORE Foundation

## Basic Interaction Models

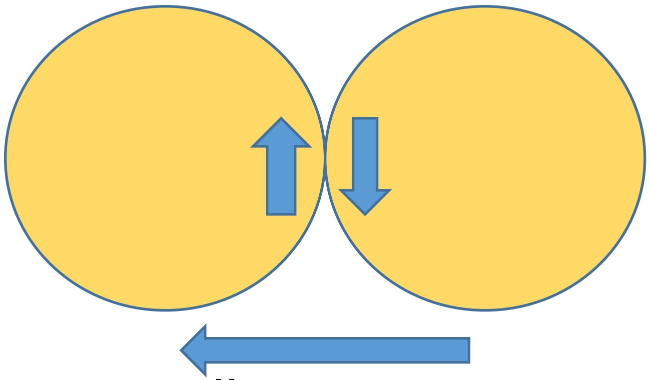
- Rolling elements
- Cage
- Outer race
- Inner race
- Other external components



# ADORE Foundation

## Bearing Cage – Primary Purpose

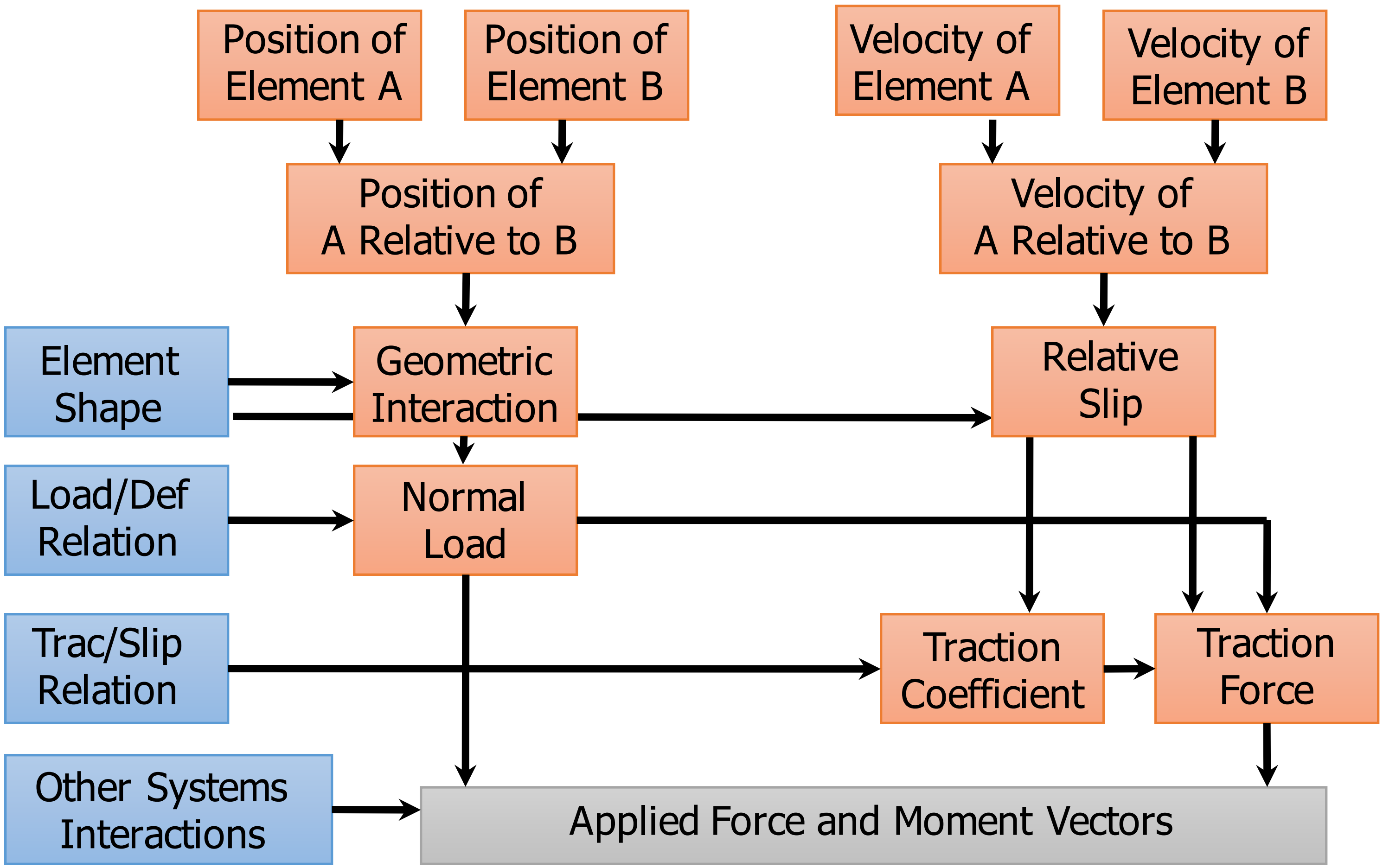
- Eliminate high-speed sliding contact between rolling elements




- Negative aspects
  - Stability of motion
  - Wear

# ADORE Foundation

## Interaction Model – Generic Approach



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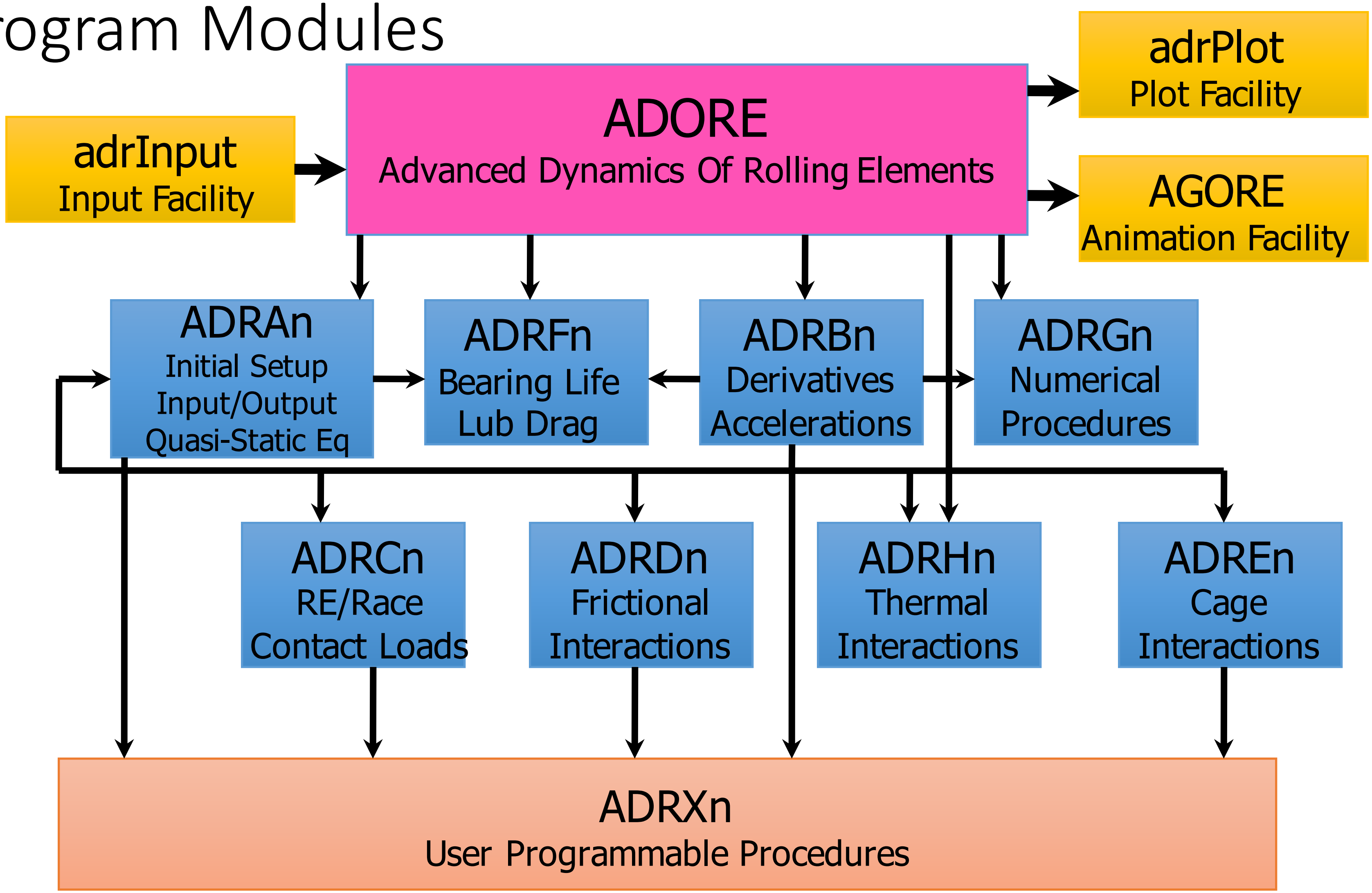
# Seminar Outline

- Day 1 – Fundamentals and ADORE overview
- Day 2 – ADORE input/output and user instructions
- Day 3 – Dynamic Concepts & Interaction Models I
- Day 4 – Interaction Models II and Other Codes
- Day 5 – Design Procedures and Examples

# ADORE Development

## Program Modules



# ADORE Technical Development

## Day 2: ADORE Input/Output & User Instructions

- ADORE Data Files
- ADORE Input – Program Input and Control
    - Short Break
- ADORE Input – Bearing Geometry
- ADORE Input – Material Properties
- ADORE Input - Operating Conditions
- ADORE Input – Frictional Interactions
    - Lunch Break
- ADORE Print Output
- ADORE Plot Output
    - Short Break
- Graphic Animation - AGORE

# Data File Management

## ADORE Data Sets

| Device | File Name | Description |
|---|---|---|
| 2 | DATA.txt | Input data file |
| 3 | PRINT.txt | Print output |
| 7 | MASTER | Input data and last solution vector |
| 8 | FINAL | Arbitrary initial conditions vector |
| 11 | SOL1 | Plot data for element #1 |
| 12 | SOL2 | Plot data for element #2 |
| 13 | SOL3 | Plot data for element #3 |
| 14 | SOL4 | Plot data for element #4 |
| 15 | SOL5 | Plot data for element #5 |
| 16 | SOL6 | Plot data for element #6 |
| 17 | SOL7 | Power dissipation and life data |
| 18 | SOL8 | Graphics animation data |
| 19 | SOL9 | Optional user output data |

# Data File Management

## Basic File Structure

- All data in readable text files
- Typical Views
  - Input file – DATA.txt
  - Output file – PRINT.txt

# ADORE Input

| Rec # | |
|---|---|
| 1 | Program mode, output control and integration method |
| 2 | Step size information and thermal modeling |
| 3 | Run identification and options |
| 4 | Overall size and external environment |
| 5 | Bearing geometry |
| 6 | Optional inertial parameters |
| 7 | Cage geometry |
| 8 | Material properties |
| 9 | Operating conditions |
| 10 | Lubricant traction and frictional behavior |
| 11 | Gravity effects |
| 12 | Input for user programmable subroutines |

# ADORE Input

## ADORE Input Facility AdrInput

- Java based interactive facility
- Automatic selection of data records
- Prepares the editable input text file
- ADORE Input may be best reviewed by executing the input facility

# ADORE Input
## Program Input and Control

- Records 1, 2 and 3
- **Execute AdrInput**

# Element Numbering

- Rolling elements: 1 to nRe
- Cage: nRe+1
- Outer race: nRe+2
- Inner race: nRe+3

# ADORE Technical Development

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# ADORE Input
## Bearing Geometry

- Records 4, 5, 6 and 7
- **Continue with AdrInput execution**

# ADORE Input

## Material Properties

- Record 8
- Required when user supplies materials data
- **Continue with AdrInput execution**

# ADORE Input
## Operating Conditions

- Record 9
- **Continue with AdrInput execution**

# ADORE Input
## Frictional Interactions

- Hypothetical models
- Elastohydrodynamic models
  - Simplified Newtonian models
  - Visco-elastic models
  - Shear-thinnng models
    - Presently in development stage

# ADORE Input

## Frictional Interactions & Gravity Effects

- Records 10 and 11
- **Continue with AdrInput execution**

# ADORE Input
## Inputs for User Programmable Procedures

- Record 12
- As programmed by the user
- Data must be manually appended to the input text file prepared by AdrInput

# ADORE Technical Development

## Day 2: ADORE Input/Output & User Instructions

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# ADORE Print Output

- Nominal data
  - Input data listing
  - Bearing geometry
  - Material properties
  - Inertial parameters
  - Lubrication parameters
  - Fatigue parameters
  - Initial operating conditions
  - Scale factors and output control
- Stiffness-speed table
- Quasi-static output
- Dynamic output
  - Rolling element parameters
  - Race and cage parameters
  - Applied parameters
  - Time step summary
- Run Statistics

# ADORE Print Output
## Typical Output File

- View PRINT.txt file

# ADORE Plot Output

- Power dissipation and life
- Rolling element motion
- Cage motion
- Race motion

# ADORE Plot Output
## Power Dissipation and Life

- Bearing life and power loss
- Applied moments on the races
- Time-averaged wear rates
- Bulk temperatures of bearing elements

# ADORE Plot Output

## Rolling Element Motion

- Mass center acceleration
- Mass center velocity
- Mass center position
- Angular orientation
- Angular velocity
- Contact loads, angles and spin/roll ratios
- Contact slip, heat generation and lubricant film
- Roller/flange interactions

# ADORE Plot Output

## Cage Motion

- Mass center velocity
- Cage/race interaction
- Mass center acceleration
- Mass center whirl orbit
- Mass center position
- Angular velocity
- Cage pocket interactions

# ADORE Plot Output

## Race Motion

- Mass center velocity
- Applied forces
- Applied moments
- Mass center acceleration
- Mass center orbit
- Mass center position
- Angular orientation
- Angular velocity

# ADORE Plot Output
## Plot Facility AdrPlot

- Java based application
- Interactive selection of plot data
- **Execute AdrPlot**

# ADORE Technical Development

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# Graphic Animation AGORE

## Basic Approach

- Draw element shape
  - Use available bearing geometry data
  - Save all shapes
- At given time step collect element position from ADORE data base
- Place element at prescribed position
- Repeat the process at next step and continue the process

# Graphic Animation AGORE

## ADORE Data Base

- Output file SOL8
- All bearing geometry data
- All coordinates as a function of time
- Depending on number of time steps the file size can be quite large

# Graphic Animation AGORE
## Animated Graphics Of Rolling Elements

- Java based application
- Interactive selection of ADORE data set
- Animated views of bearings elements
- Execute AGORE

# ADORE Technical Development

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# ADORE Technical Development

## Day 3: Dynamics Concepts & Interaction Models I

- ADORE base formulation
- Fundamentals in dynamic modeling
- Dimensional organization
- Numerical considerations
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# Base Formulation

## System of First Order Differential Equations

- Second order differential equation of motion reduced to first order equations

$$m\ddot{x} = F \Rightarrow \begin{array}{l} m\dot{v} = F \\ \dot{x} = v \end{array}$$

- Generalized six-degrees-of-freedom yield 12 equations per bearing element

# Base Formulation

## Position and Derivative Vectors

$$\text{Position Vector} = \mathbf{X} = \begin{Bmatrix} x \\ r \\ \theta \\ \dot{x} \\ \dot{r} \\ \dot{\theta} \\ \eta \\ \xi \\ \zeta \\ \dot{\eta} \\ \dot{\xi} \\ \dot{\zeta} \end{Bmatrix}$$

$$\text{Derivative Vector} = \mathbf{Y} = \begin{Bmatrix} \dot{x} \\ \dot{r} \\ \dot{\theta} \\ \ddot{x} \\ \ddot{r} \\ \ddot{\theta} \\ \dot{\eta} \\ \dot{\xi} \\ \dot{\zeta} \\ \ddot{\eta} \\ \ddot{\xi} \\ \ddot{\zeta} \end{Bmatrix} \Leftarrow \mathbf{F}$$

12 Differential Equations per Bearing Element

# Generalized Vectors

$$i = 1, N$$

$N =$ Number of Rolling Elements + Number of Cage Segments + 2

Genealized Position Vector $= \mathbf{X} = \begin{Bmatrix} t \\ .. \\ x_i \\ r_i \\ \theta_i \\ \dot{x}_i \\ \dot{r}_i \\ \dot{\theta}_i \\ \eta_i \\ \xi_i \\ \zeta_i \\ \dot{\eta}_i \\ \dot{\xi}_i \\ \dot{\zeta}_i \\ .. \end{Bmatrix}$

Generalized Derivative Vector $= \mathbf{Y} = \begin{Bmatrix} 1 \\ .. \\ \dot{x}_i \\ \dot{r}_i \\ \dot{\theta}_i \\ \ddot{x}_i \\ \ddot{r}_i \\ \ddot{\theta}_i \\ \dot{\eta}_i \\ \dot{\xi}_i \\ \dot{\zeta}_i \\ \ddot{\eta}_i \\ \ddot{\xi}_i \\ \ddot{\zeta}_i \\ .. \end{Bmatrix} \Leftarrow \mathbf{F}$

Number of Equations $= 1 + N * 12$

# Dynamics Modeling
## Some fundamental concepts

- Differential equations of motion are integrated in time domain
- Often carried out numerically
- System characteristics controls permissible step size in numerical integration
- Based on system behavior time step size may be dynamically altered
- Truncation error must be bounded for acceptable convergent solutions

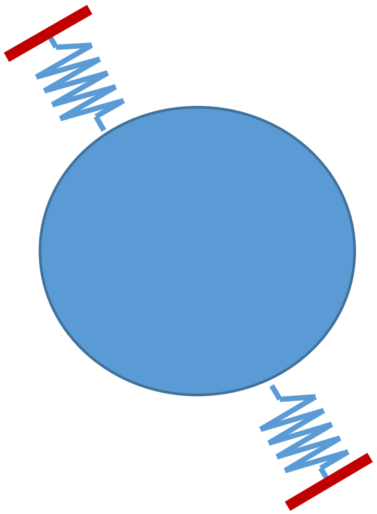
# Dynamics Modeling
## Some fundamental concepts

- Generalized motion with no constraints
  - Multiple characteristics frequencies in spectrum
  - Sometimes wide spectrum
  - Rolling bearing systems is generally ”stiff”
    - Dominant frequencies are far apart
- Constrained motion
  - Selective suppression of certain frequencies
  - Works very well with stiff systems
- Numerical simulation
  - Step size must permit simulation of highest frequency
  - Truncation error must be bounded

# Dynamics Modeling

## Rolling Bearings

- Highest frequency corresponds to rolling element to race contact vibration
- Next dominant frequency is the kinematic frequency
  - Oscillation of ball is race groove
- Numerical step size may be no larger than half the wave length of this frequency
- Equilibrium constraint could eliminate these frequencies to provide larger time step



# Dynamics Modeling
## Dimensional Organization

- System of units
- Large versus small bearings
- Truncation error
  - Controlled by step size optimization algorithms
  - Tracking discontinues in system behavior
- Numerical round-off and truncation
  - Set by machine precision

# Dynamics Modeling
## Dimensional Organization

- Meaningful truncation error controls requires that that all variables must be dimensionless
- Fundamental scales in rolling bearings
  - Time – Wave length of highest frequency
  - Length
    - Often arbitrary (ADORE ⇒ Rolling element radius)
  - Force
    - Often arbitrary (ADORE ⇒ Largest load)
- Above yields rolling elements with unit radius and mass

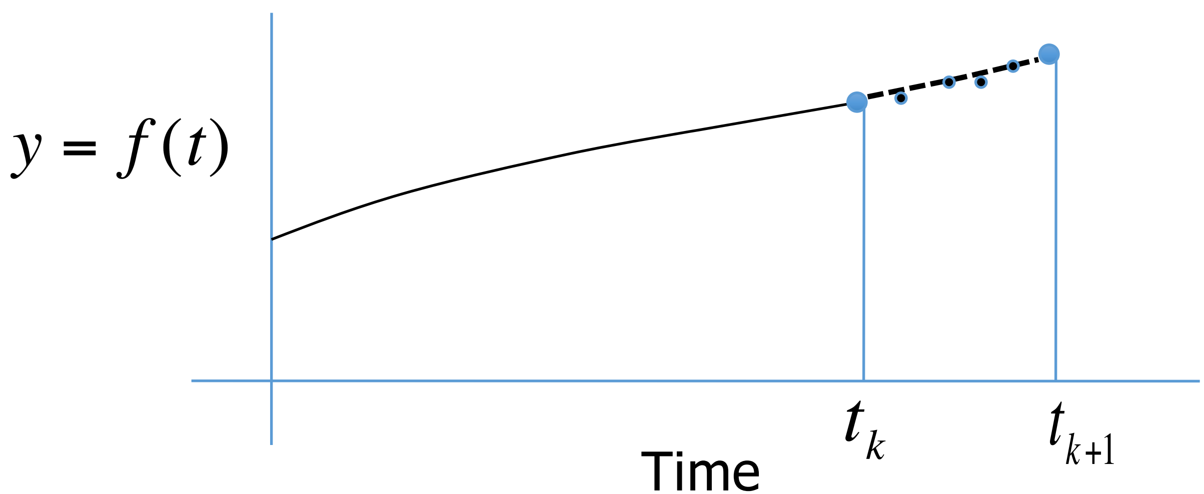
# Dynamics Modeling
## Numerical Considerations

- System of first order differential equations
- Explicit Runge-Kutta-Fehlberg algorithms
- Implicit Predictor-Corrector methods
- Truncation checks
- Step size optimization

# Numerical Considerations

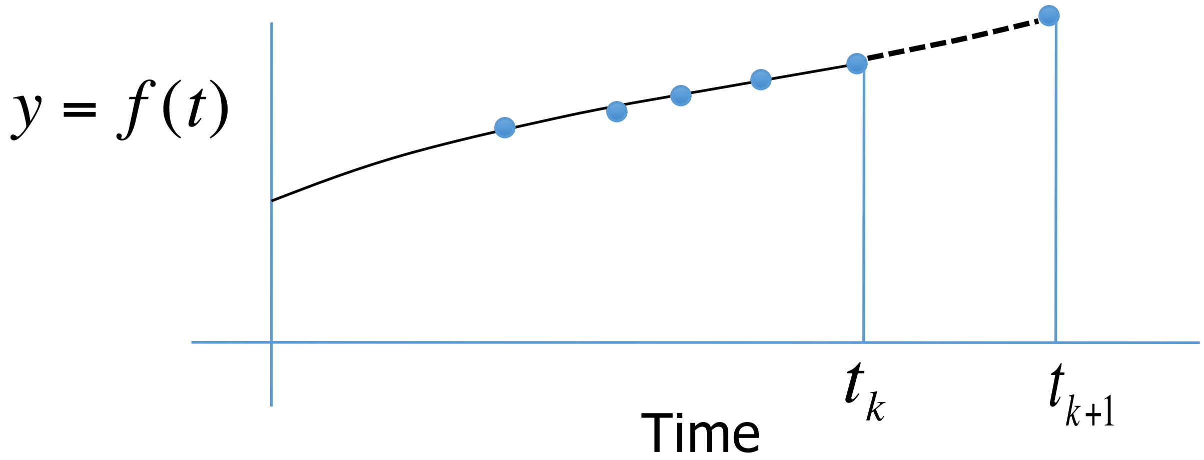
## Integrating Methods - Explicit

- Solution at a given time steps is only dependent on solutions at previous step
- Order of methods determines required intermediate solutions



# Numerical Considerations
## Implicit Methods

- Solution at a given steps depends on solutions at several previous steps
- Two-step process
    - Prediction
    - Correction



# Numerical Considerations
## Integrating Methods – ADORE Implementation

- Explicit
  - Runge-Kutta-Fehlberg
- Implicit
  - Customized method for variable step size

# Numerical Considerations
## Integrating Methods - Comparisons

| Explicit Methods | Implicit Methods |
|---|---|
| Solution depends on previous step only | Solution depends on several prior steps |
| Relatively complex procedure for truncation error computation | Truncation error easily computed |
| Any discontinuity is easily handled | Treatment of discontinuity is difficult |
| Any arbitrary variation may be easily treated | Difficult to treat high-frequency variation |
| Number of derivative per step calls increase with increasing order | Relatively small number of derivative calls |

# Numerical Considerations
## Time Variations and Step Size

- The time step size is controlled by highest frequency in the system
- Numerical integrating algorithms automatically senses the high frequency variations
- The maximum step size must be no more than one-half the wave length corresponding to the highest frequency
- ADORE limits the maximum step size to one-quarter of the wave length

# Numerical Considerations

## Step Size Optimization

- Truncation error related to step size

$$\varepsilon \sim \Delta t^n$$

- Knowing the error limit the step size could be varied

$$\frac{\varepsilon_1}{\varepsilon_2} = \left( \frac{\Delta t_1}{\Delta t_2} \right)^n$$

- For given truncation limit the maximum possible step size is always desired

# Numerical Considerations

## Step Size Optimization - Discontinuities

- Dynamic cage contacts introduce sudden discontinuities
- New rolling element to cage wall contact vibration frequency
- Reduce step size corresponding to above frequency
- Reject current solution and repeat with above step size

# Numerical Considerations

## Step Size Optimization – Numerical Control

- When actual truncation error less than the prescribed limit the next step size is increased as

$$\Delta t_j = \alpha \Delta t_{j-1} \left( \frac{\varepsilon_{\lim it}}{\varepsilon_{j-1}} \right)^{1/n}$$

$$\textbf{ADORE} \;\Rightarrow\; \alpha = 0.80$$

- Step size may vary continuously during simulation

# ADORE Technical Development

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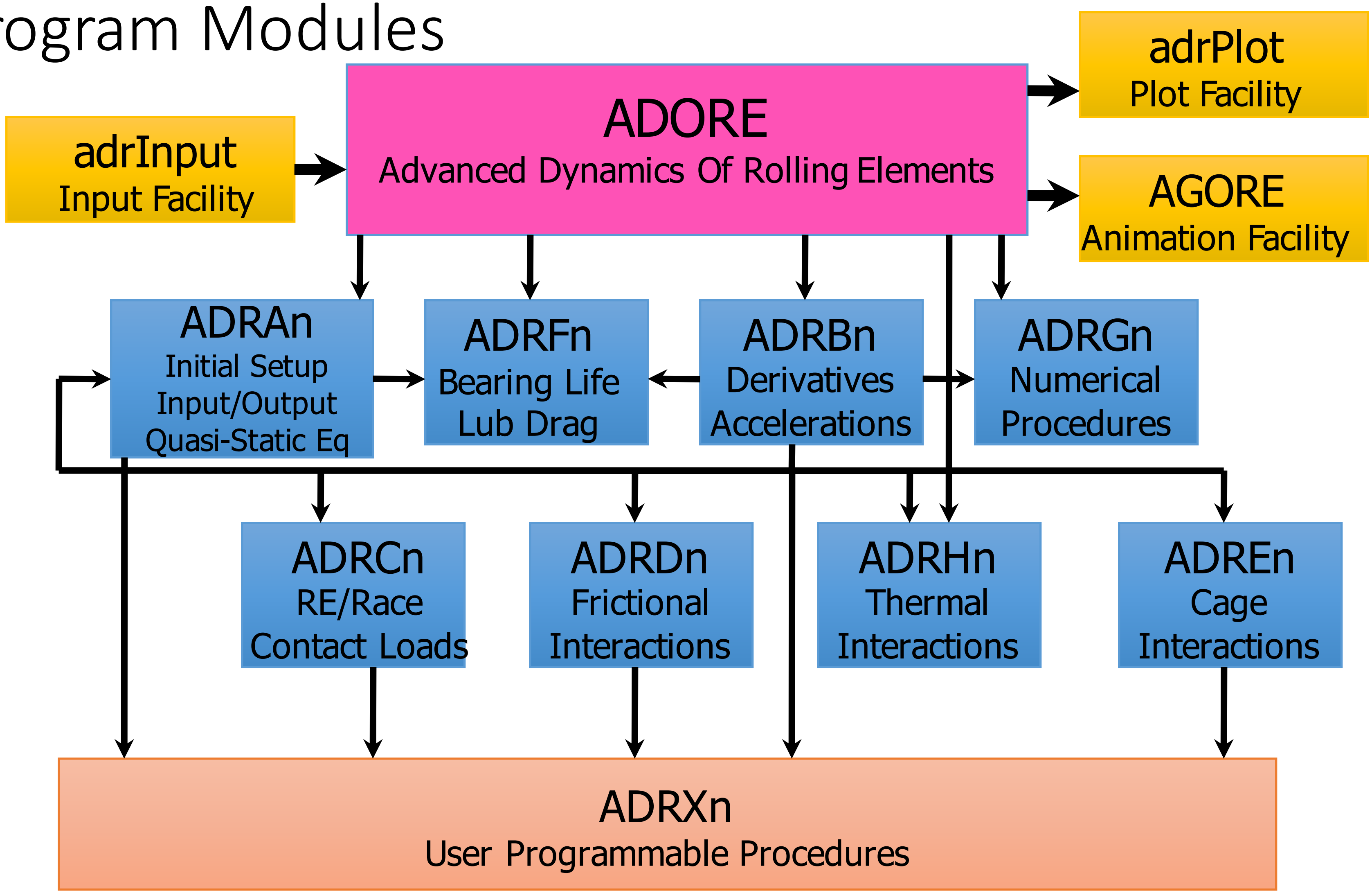
# ADORE Overview

## Program Modules

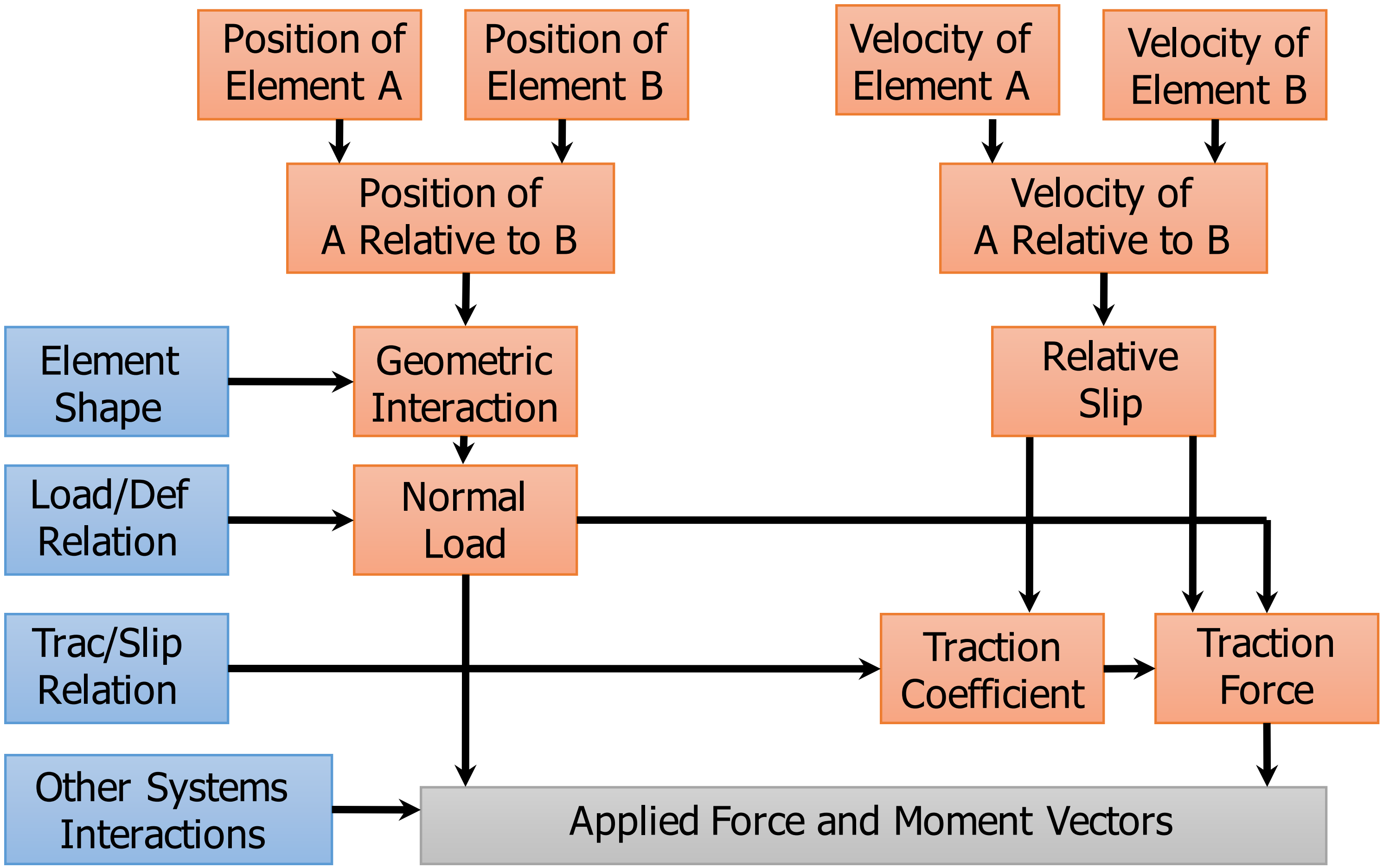


# ADORE Code Structure

## General Architecture

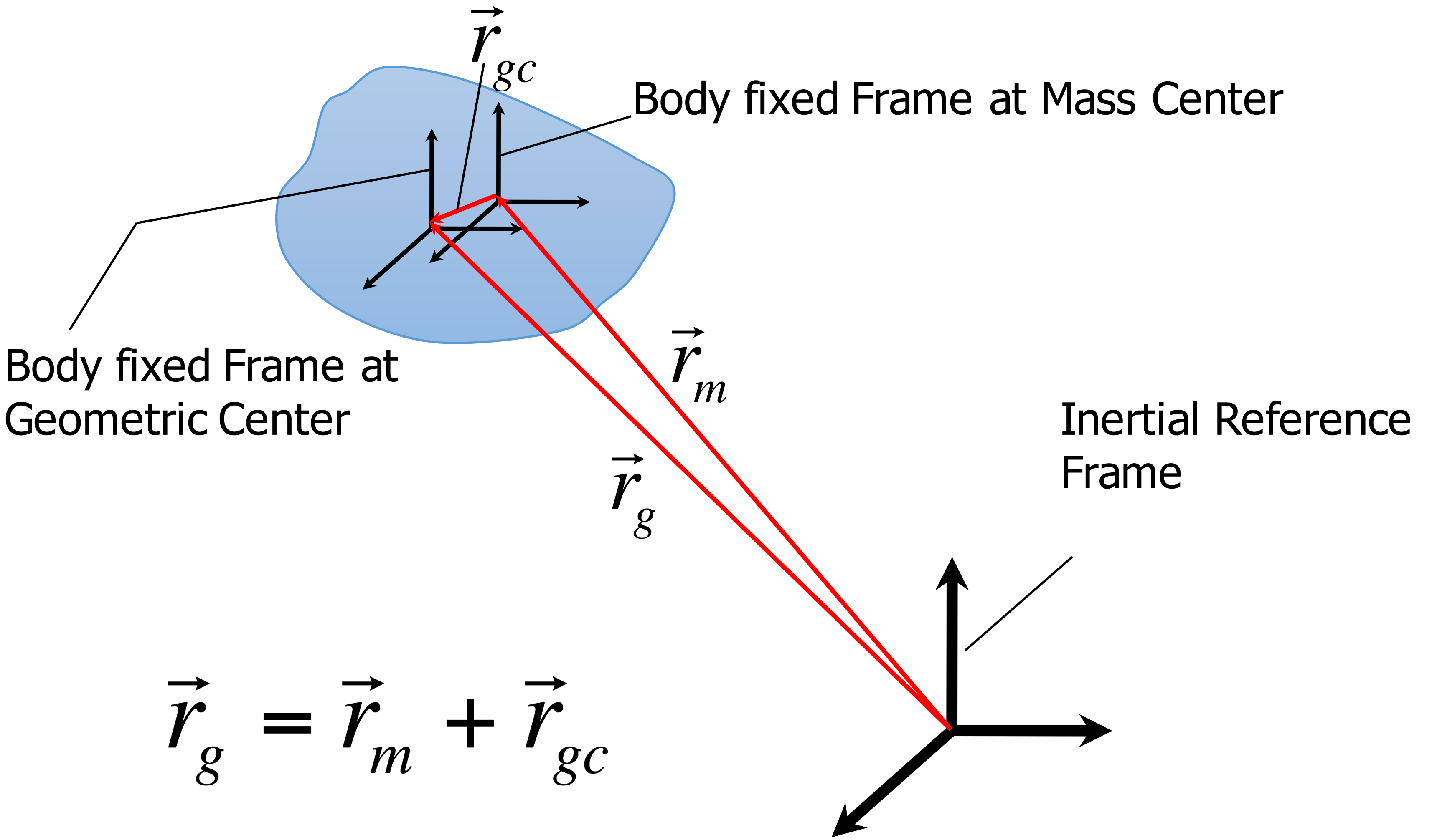
- Data Modules
- Code Modules
- External Procedures
- Internal Procedures
- **Code view**
  - **BearingGeometry**
  - **ADORE and ADRA modules**

# Interaction Modeling
## Generic Approach Recap



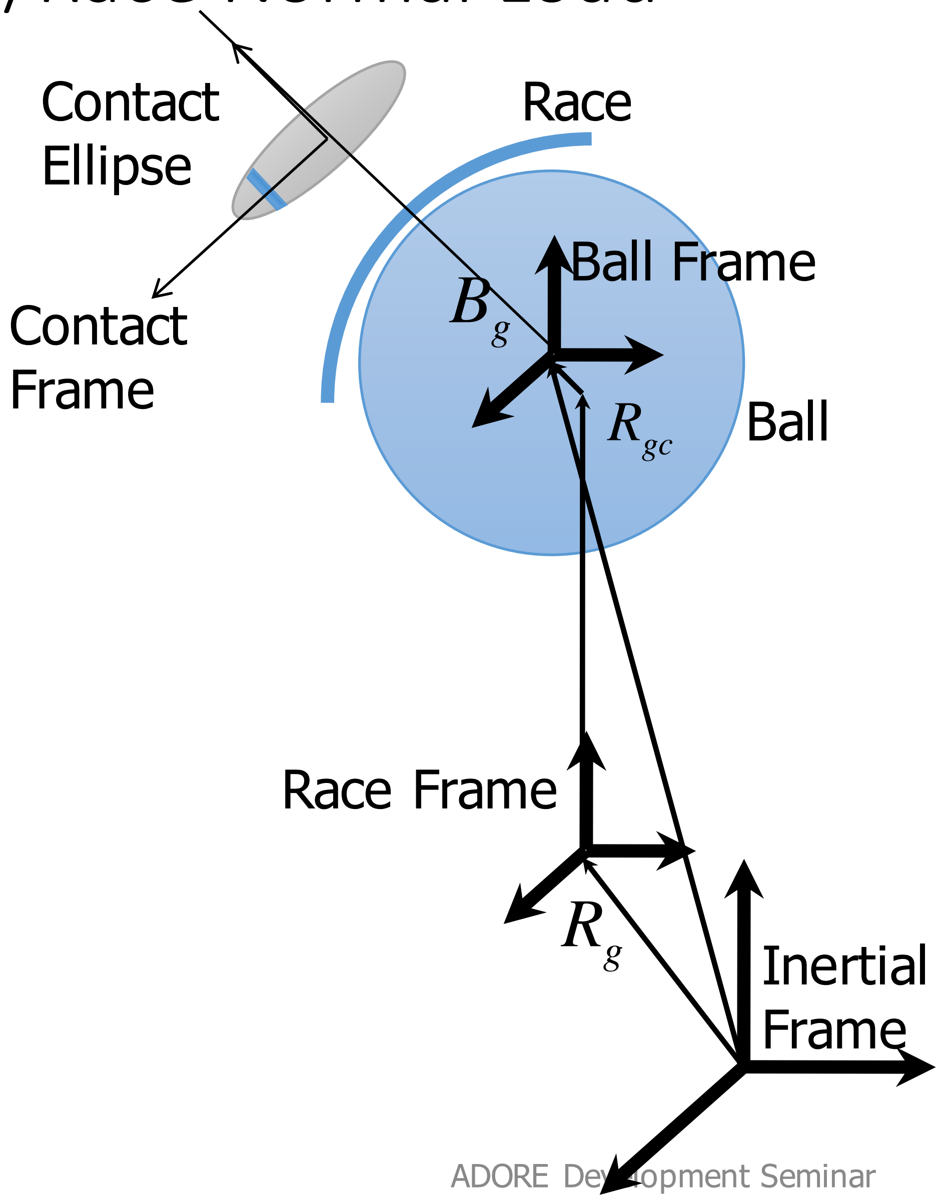
# Base Coordinate Frames

## Fundamental Properties of Solids



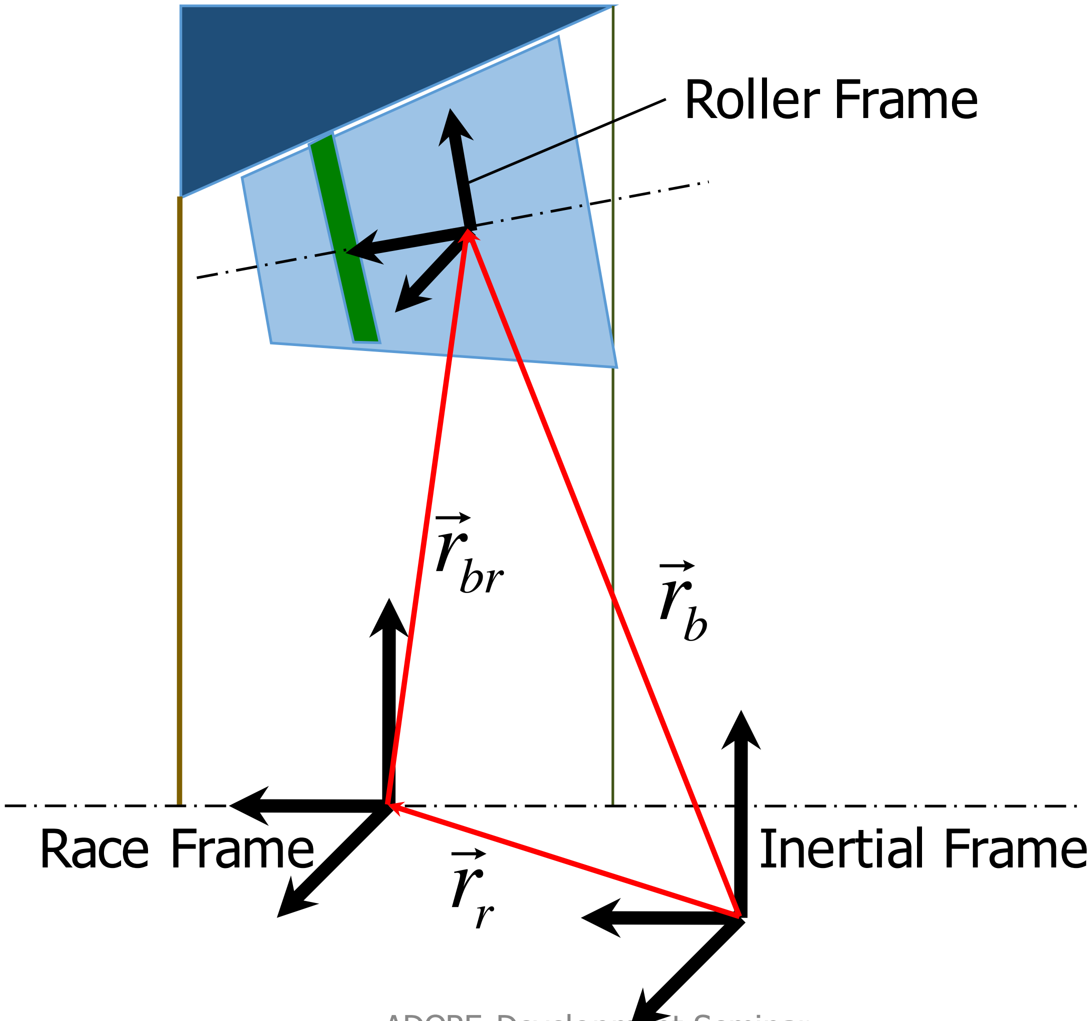

$$\vec{r}_g = \vec{r}_m + \vec{r}_{gc}$$

# Rolling Element to Race Interaction
## Ball/Race Normal Load



# Rolling Element to Race Interaction

## Roller/Race Normal Load



# ADORE Code Modules

## Rolling Element to Race Interaction

- **Code view ADRC1**

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# Frictional Interactions
## Role in Bearing Dynamics

- Perhaps the most important parameter affecting bearing motion
- Friction or traction at rolling element race contact plays a dominant role in bearing dynamics and stability of motion
  - Bearing lubrication is, therefore, a key parameter
- Cage friction is also significant in controlling cage motion and stability

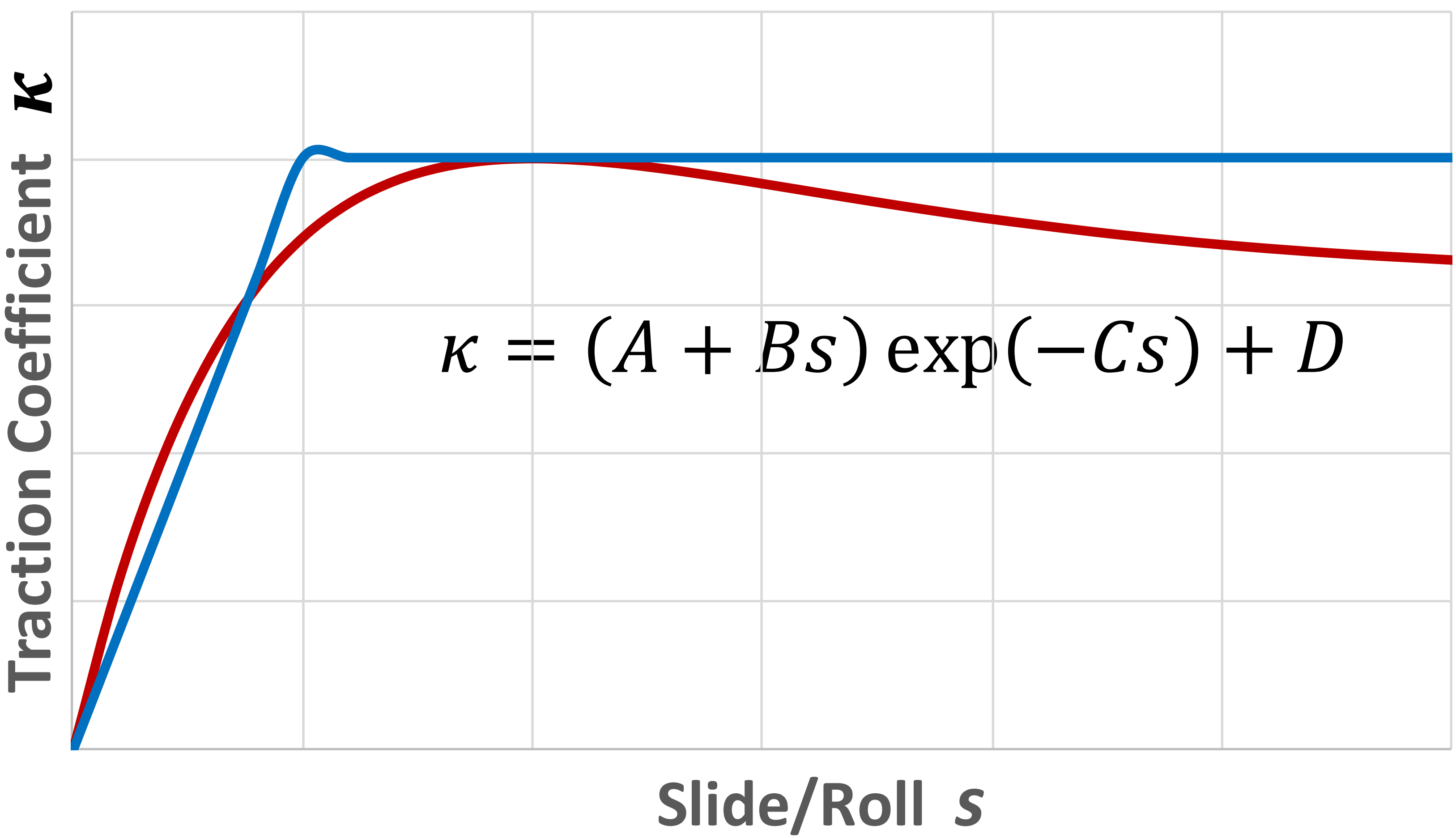
# Frictional Interactions
## Rolling Element to Race Lubrication

- Oil lubrication, common in turbine engine applications
  - Elastohydrodynamics modeling
- Solid lubrication
  - Powder or surface coatings
- Cryogenic conditions
  - Surface treatments of just dry contact

# Frictional Interactions
## Models in ADORE

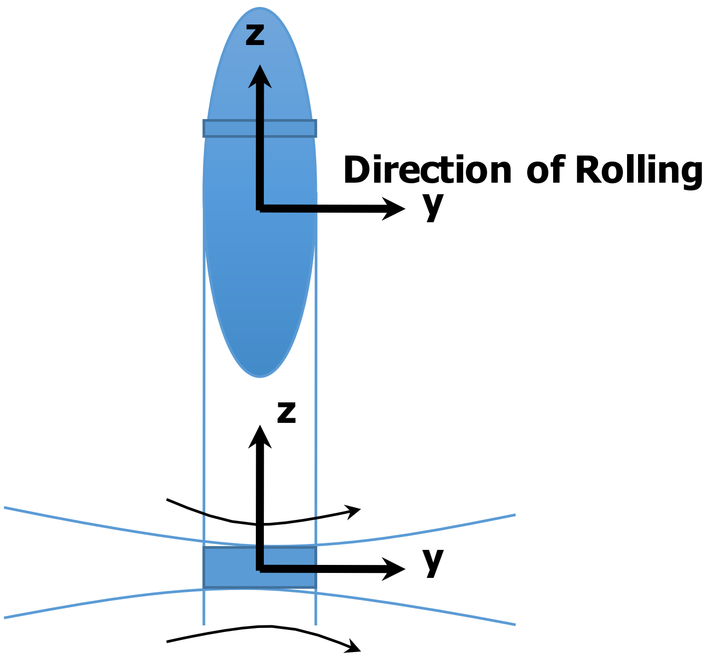
- Hypothetical models
  - Applicable to most dry or solid-lubricated contacts
- Elastohydrodynamic models
  - Simplified Newtonian models
  - Visco-elastic models
  - Shear-thinnng models
    - Presently in development stage

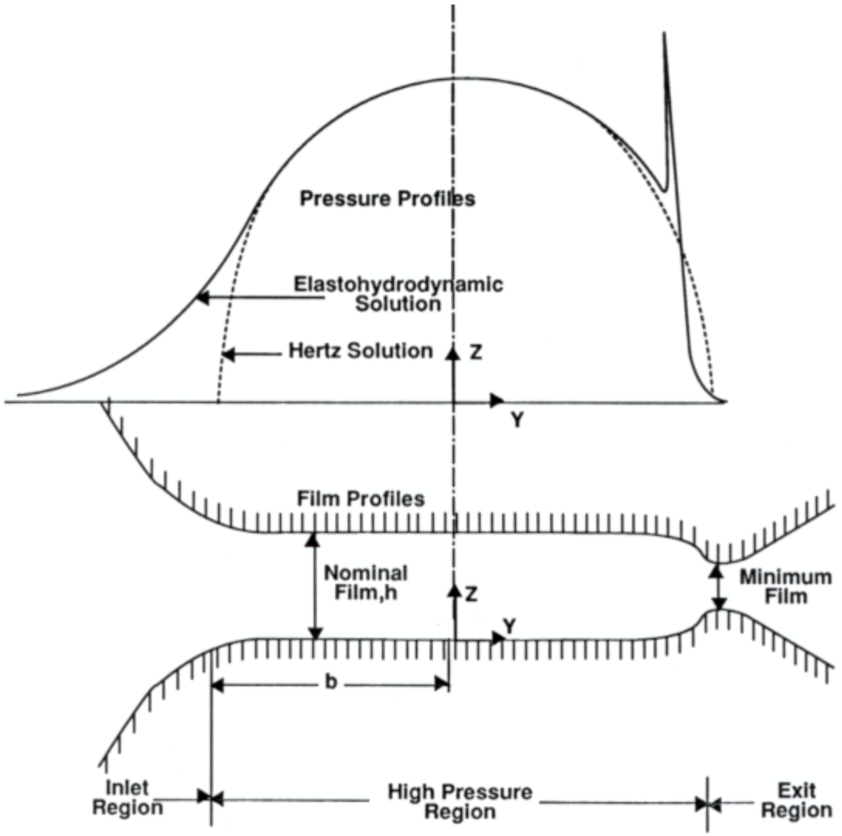
# Frictional Interactions
## Hypothetical Model



# Traction Models in ADORE

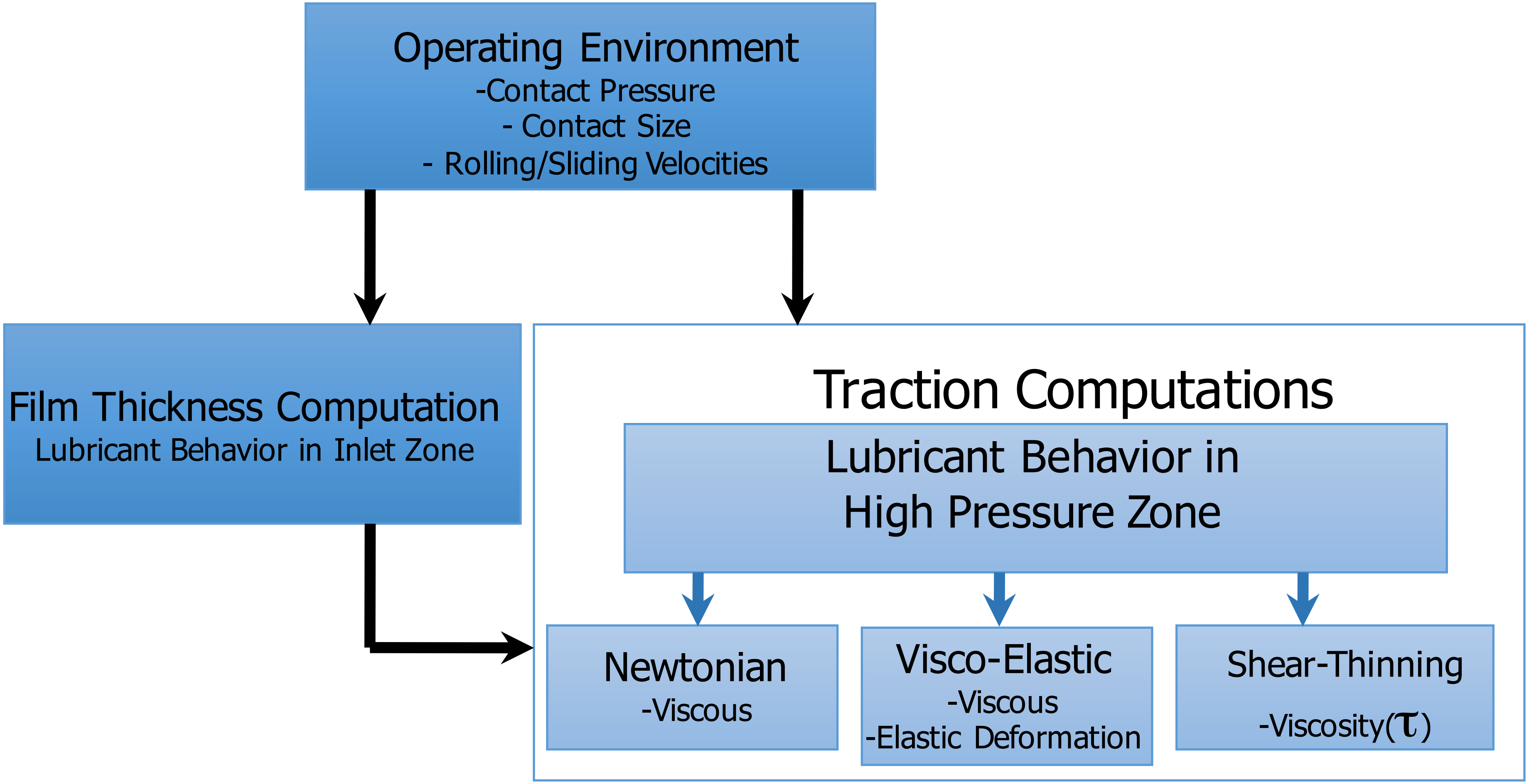
## Elastohydrodynamic Models



# Traction Models in ADORE

## Elastohydrodynamic Models – Model Schematic



# Elastohydrodynamics Models

- Newtonian $$\tau = \mu\dot{\gamma} = \mu\frac{u_s}{h} \qquad \dot{\gamma} = \frac{u_s}{h}$$
- Visco-elastic $$\dot{\gamma} = \frac{1}{G}\frac{\partial\tau}{\partial t} + \frac{\tau_o}{\mu} f(\frac{\tau}{\tau_o})$$ $$f(\frac{\tau}{\tau_o}) = a\sinh(\frac{\tau}{\tau_o})$$ $$f(\frac{\tau}{\tau_o}) = a\tanh(\frac{\tau}{\tau_o})$$
- Shear-Thinning effects
  - Newtonian with viscosity dependent on shear stress

$$\tau = \left[\phi(\tau)\mu\right]\dot{\gamma}$$

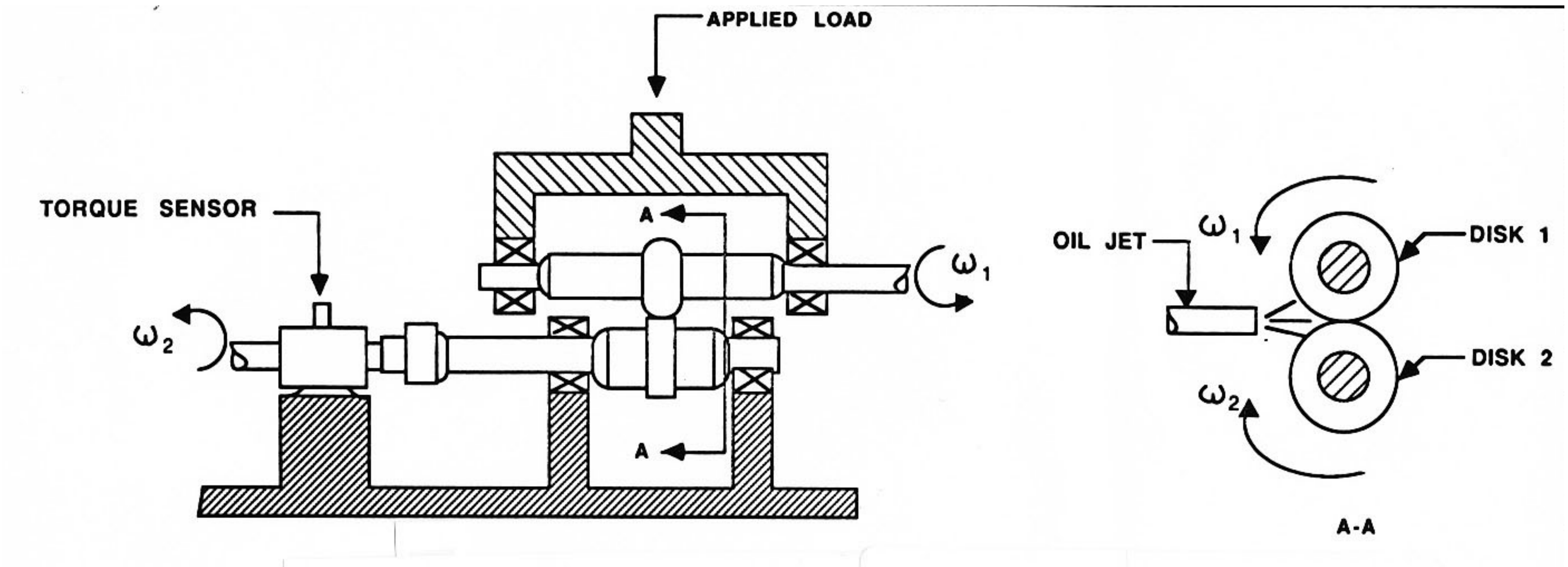
# Traction Model Development
## Fluid Lubrication

- Viscosity modeling
  - Properties supplied by manufacturers are at ambient pressure
  - May be used only for film thickness computations
- High-Pressure viscometry
  - Viscosity measurement as a function of pressure and temperature
  - Field conditions often exceed experimental limitations

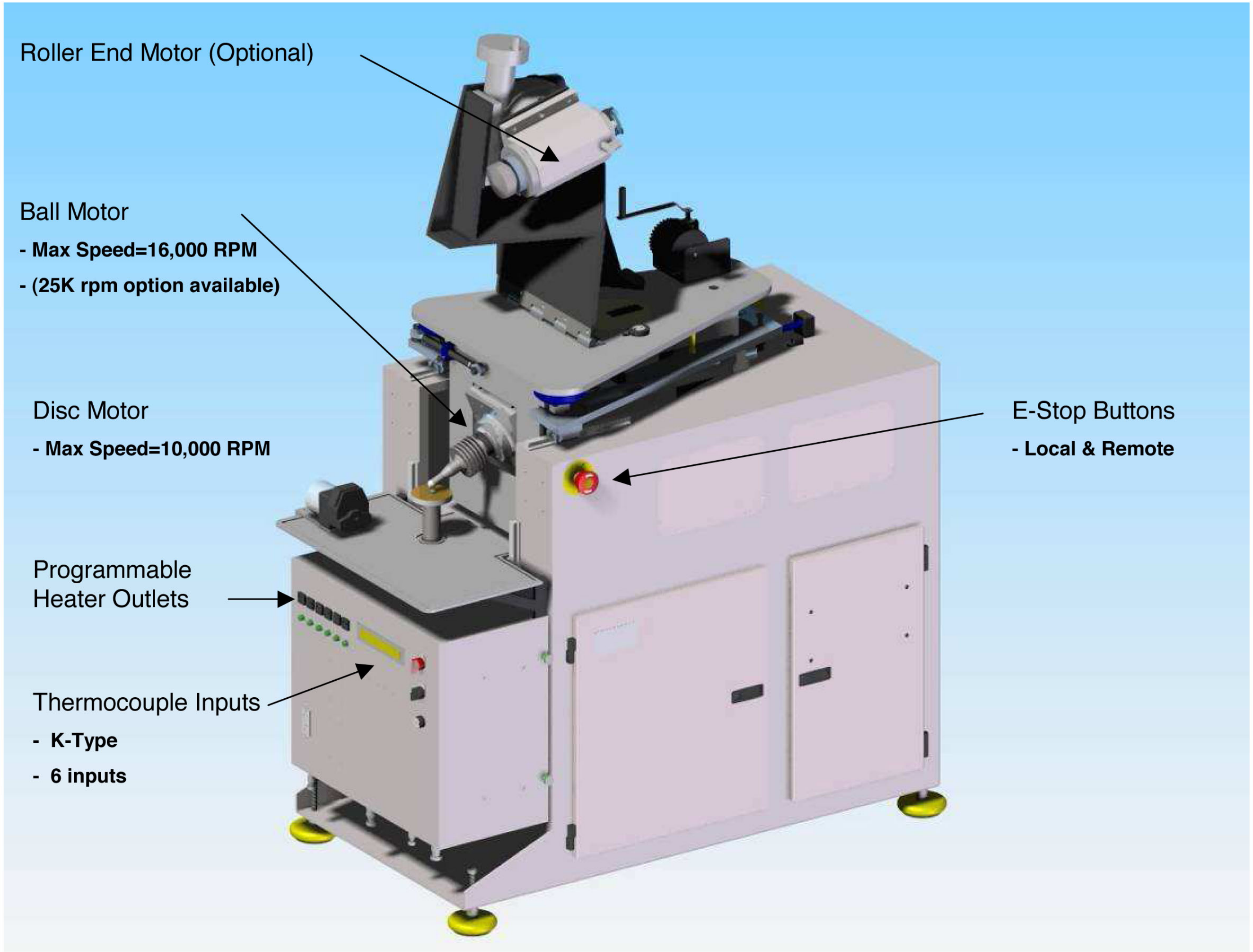
# Traction Model Development
## Fluid Lubrication

- Traction modeling
  - Empirical parameters in addition to high pressure viscosity behavior
- Experimental traction data
  - Back fit the model to derive empirical parameters
- Field conditions often exceed experimental limits

# Traction Rig
## US Air Force Cylindrical Disks



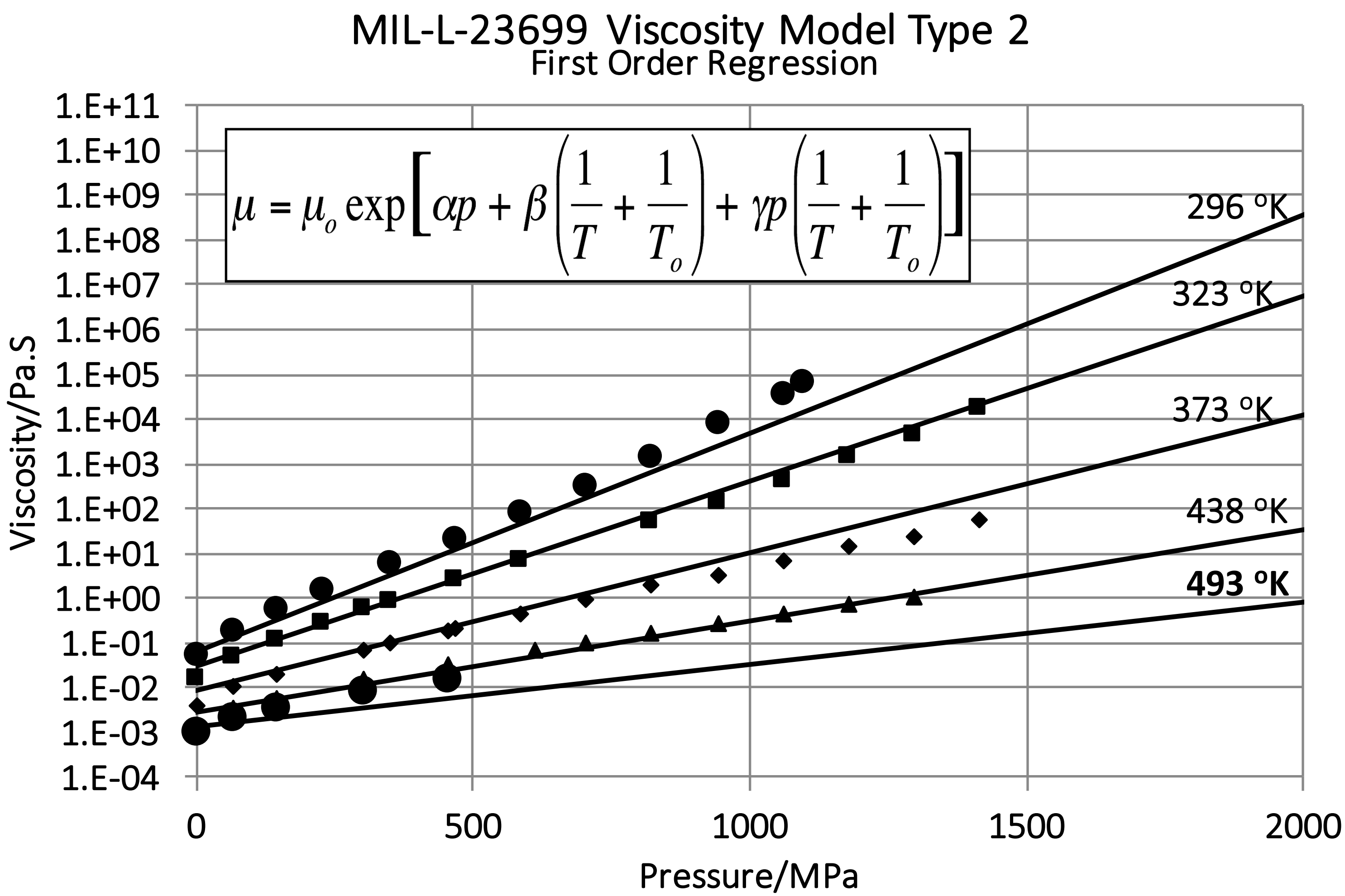
# Traction Rig
## Wedeven Associates Machine



# Traction Model Development
## Solid Lubrication and Dry Contact

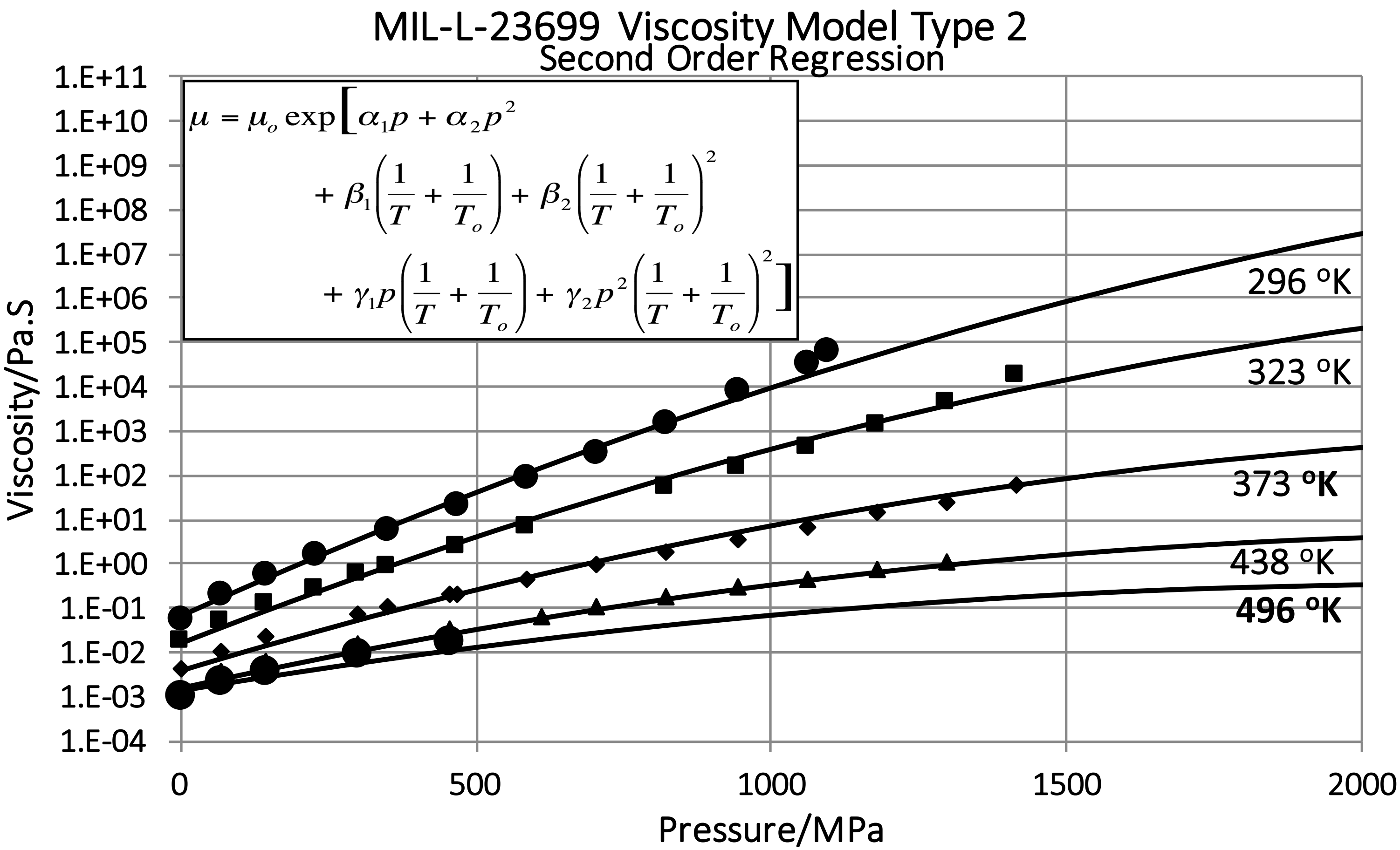
- Experimental traction data
- Generally fitted with a hypothetical model
- Normally traction slope at low slips is a key input in bearing dynamics modeling

# Traction Modeling
## Viscosity modeling – Simple polynomial

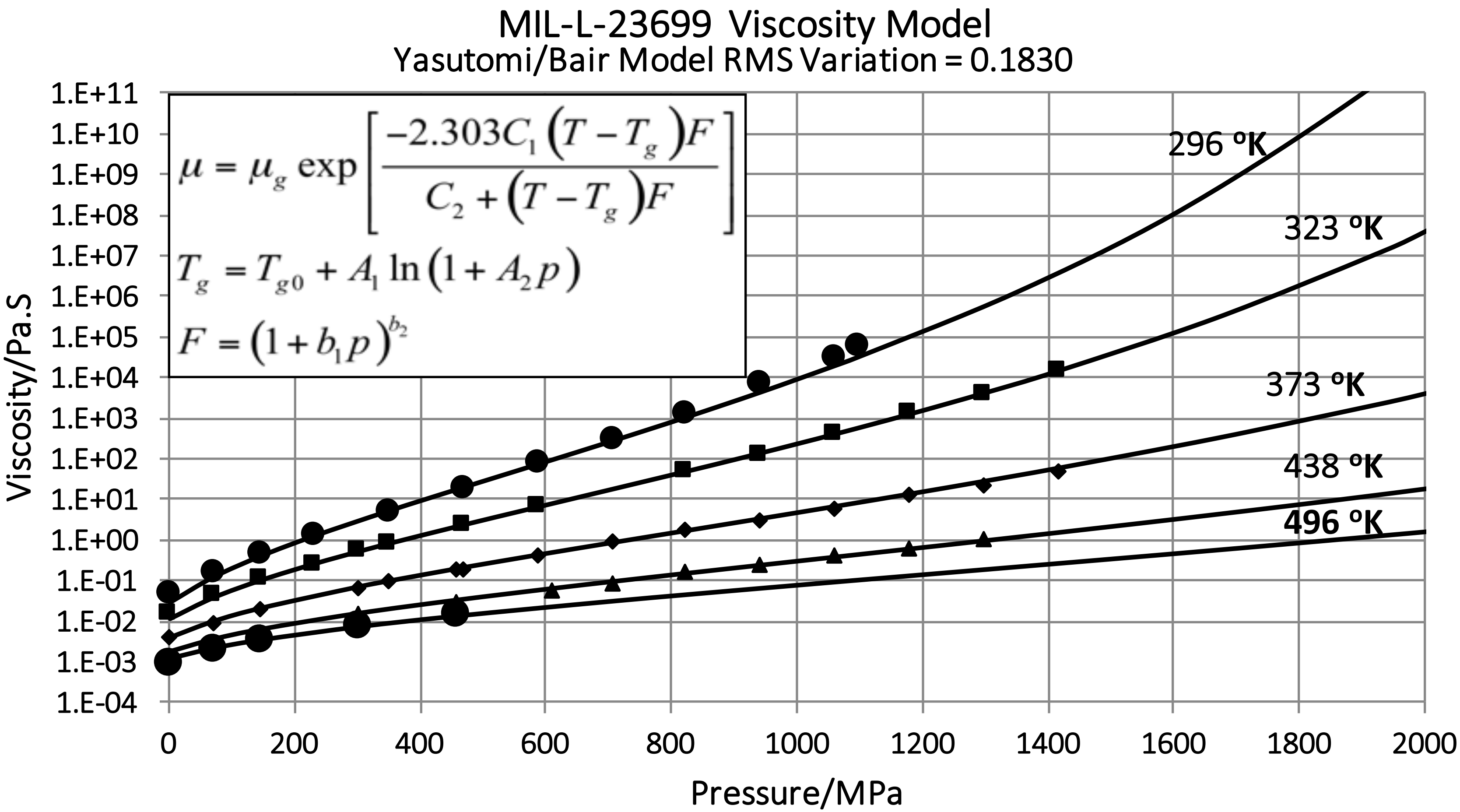


# Traction Modeling

## Viscosity modeling – Simple polynomial



# Traction Modeling
## Viscosity modeling – Yasutomi/Bair



# Traction Modeling

## Shear-Thinning model highlights (MIL-L-23699)

- Carreau equation

$$\tau = \left[\mu \frac{u_s}{h}\right]\left[1 + \left(\frac{\mu}{G}\frac{u_s}{h}\right)^2\right]^{\frac{n-1}{2}}$$

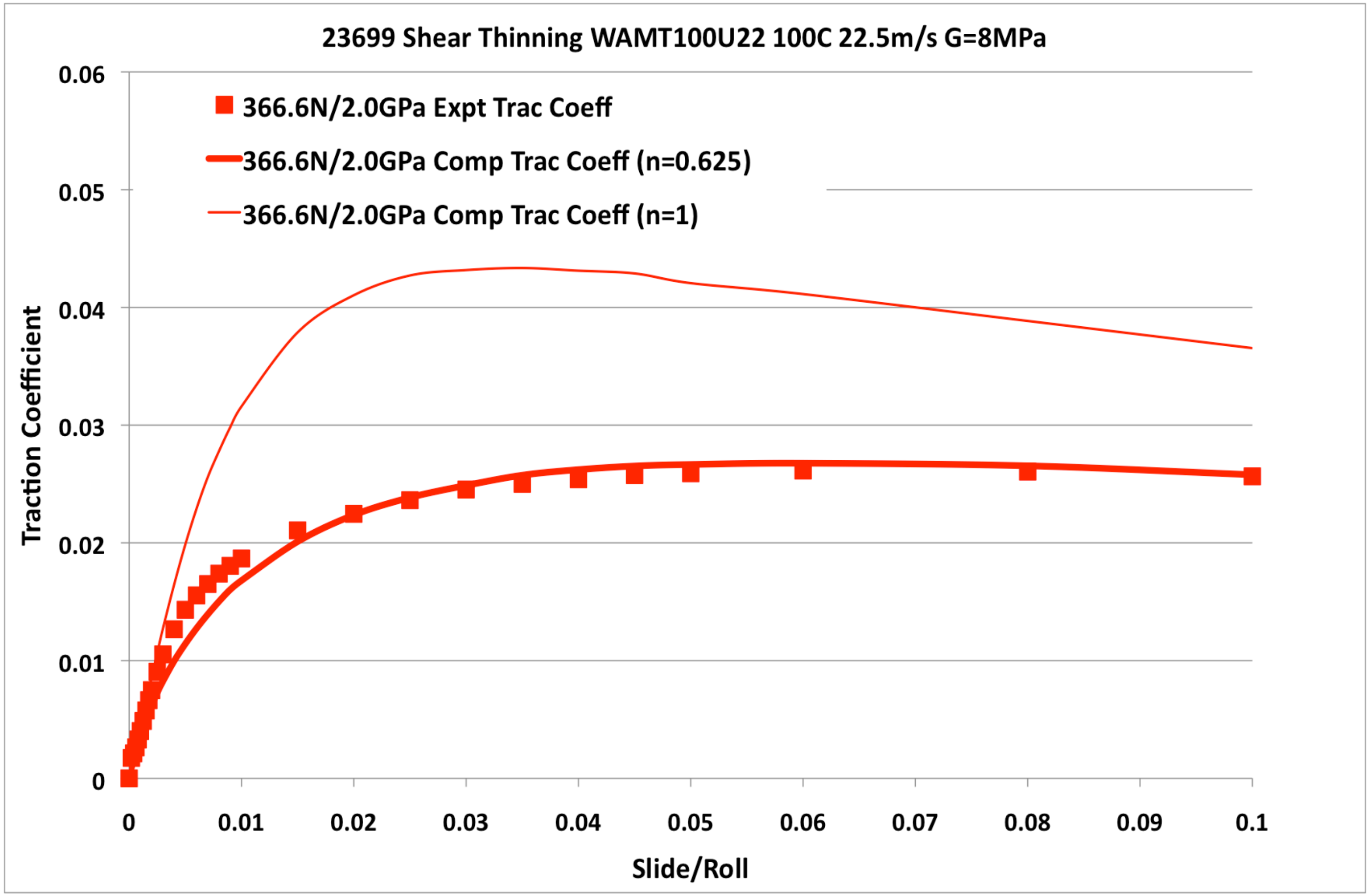
  - $n = 1$ makes the behavior Newtonian

- Thermal interaction

$$\Delta T = \frac{\tau u_s h}{4K}$$

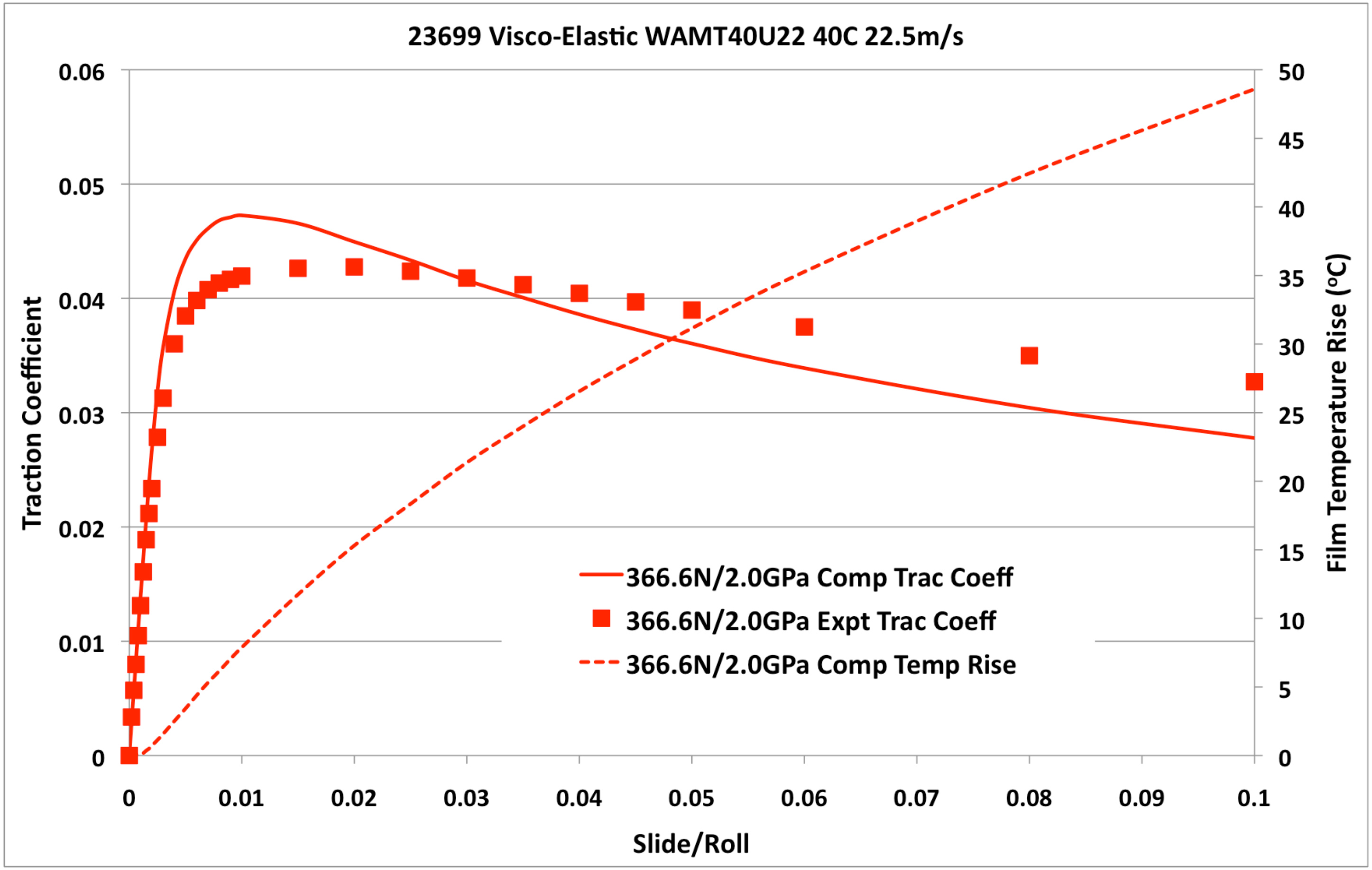
- Iterative solutions to obtain compatible temperature and shear stress

# Shear Thinning Model
## Typical Correlation with Experimental Data



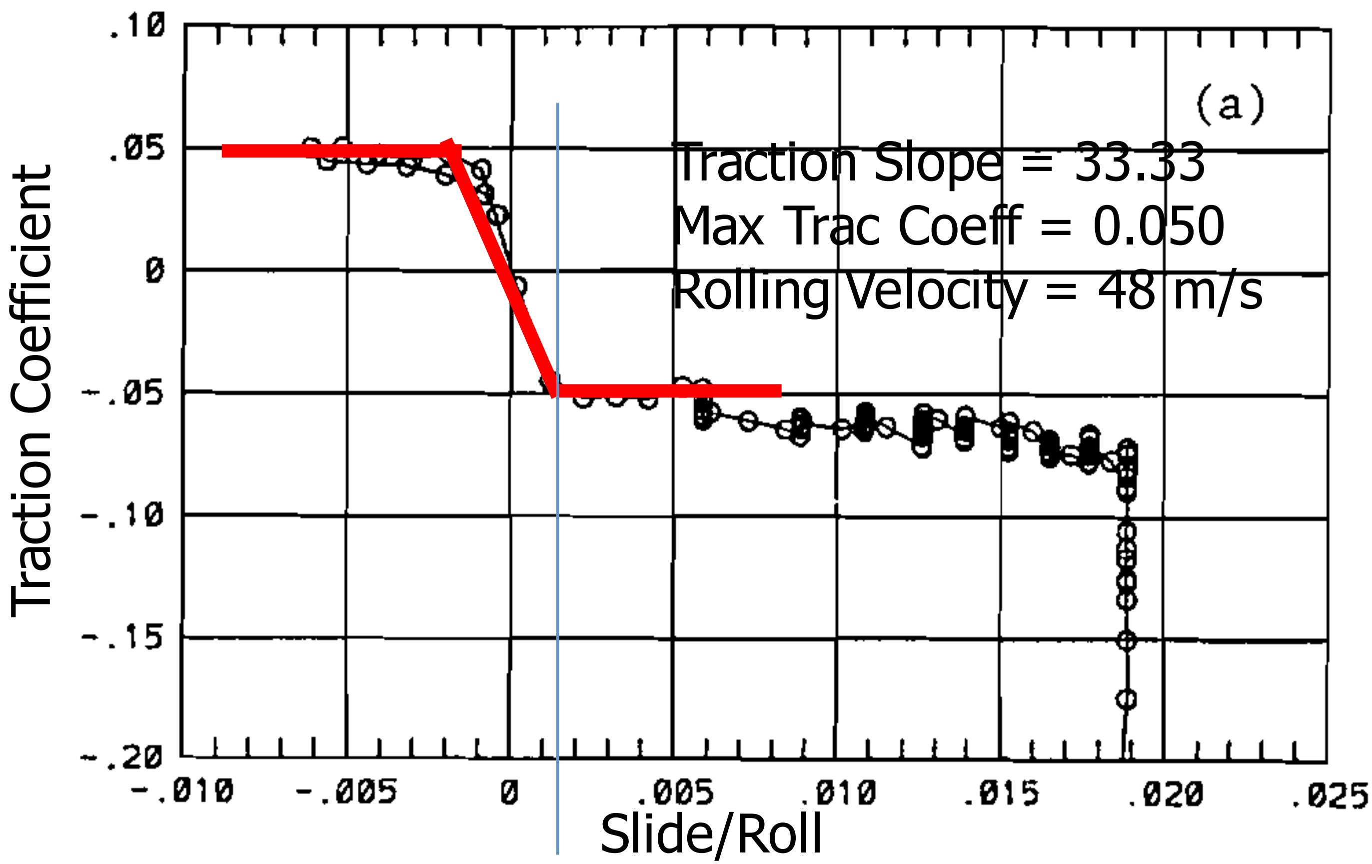
# Visco-Elastic Model

## Typical Correlation with Experimental Data



# Traction Modeling

## Cryogenic Conditions – Traction Data in LOX




Chang, Hall & Thom, STLE Trans 41(1), 87-95, 1998

# Rolling Element to Race Interaction
## Traction or Frictional Interactions

- ADORE procedures ADRD
  - **Code view ADRD1**

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# Frictional Interactions
## Rolling Element to Race Traction

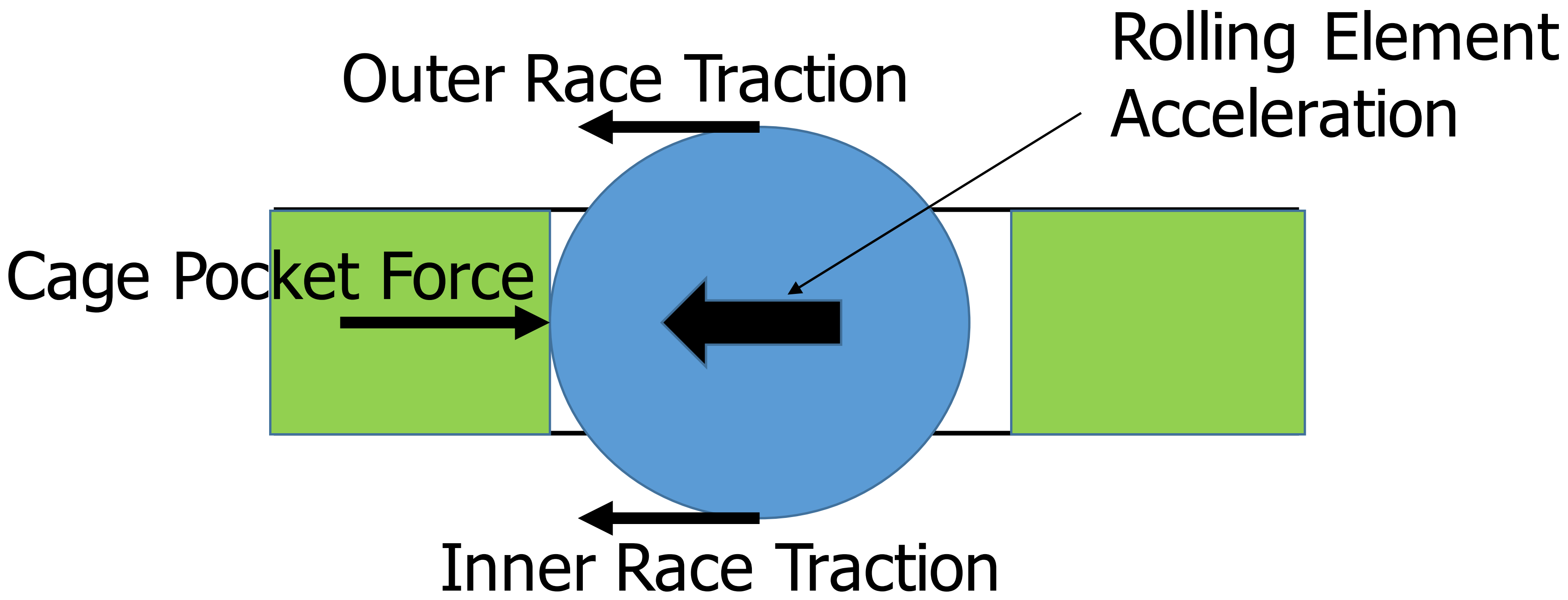
- Contributes to bearing heat generation
  - May contribute to fluid evaporation in cryogenic environment
- Affects bearing and lubricant temperature, which in turn
  - Alters effective lubricant properties
  - Alters bearing operating geometry
- Contributes to rolling element orbital acceleration
- Thereby affects cage pocket force
- Traction-Slip coupling controls stability of motion
  - Both rolling elements and cage

# Frictional Interactions

## Cage Friction

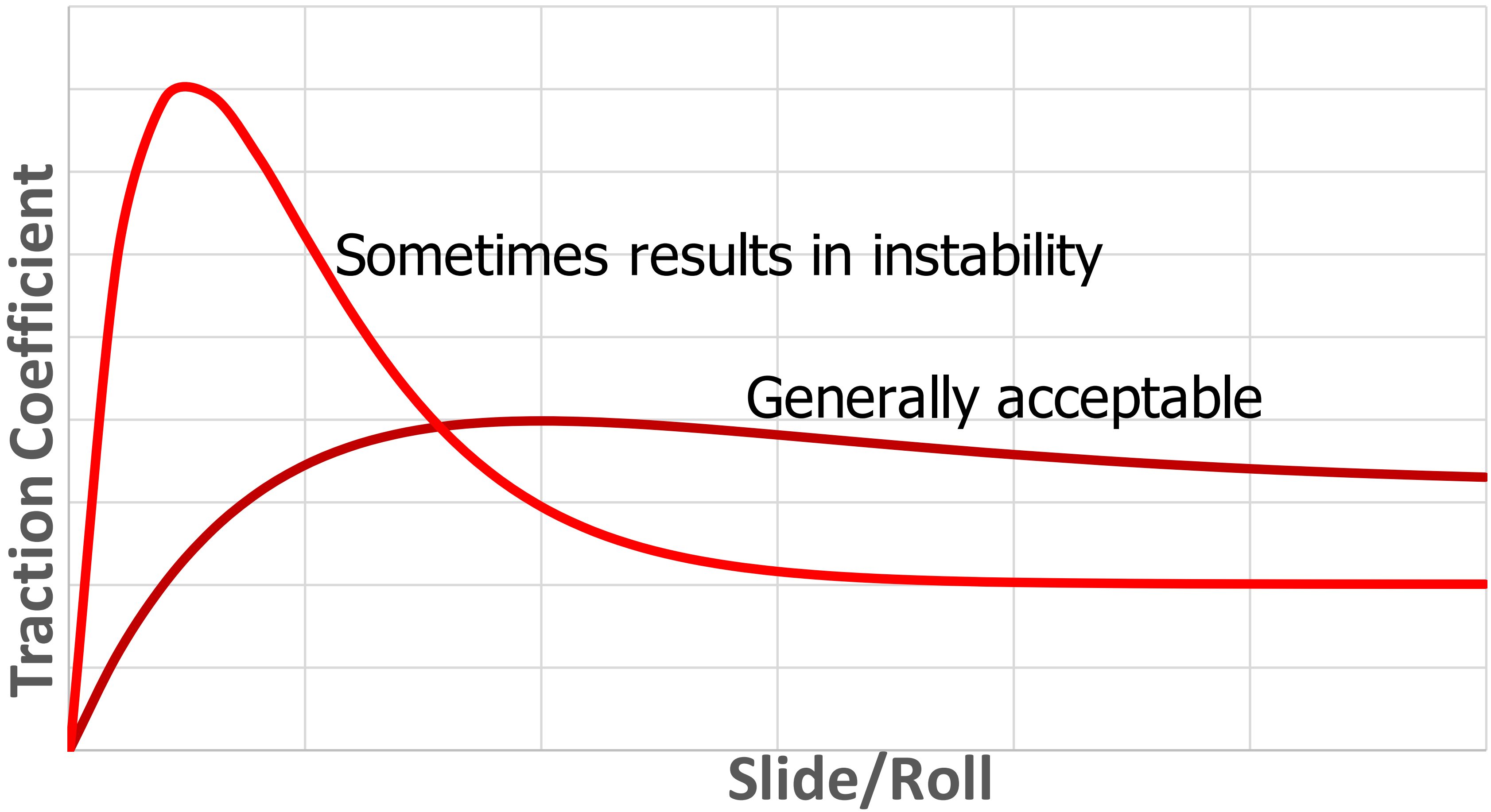
- Generally a high sliding contact
  - Assumption of constant friction coefficient is reasonable
- Affects rolling element angular acceleration
- Promotes cage whirl
- Affects overall cage stability

# Frictional Interactions
## Significance in Dynamics Modeling



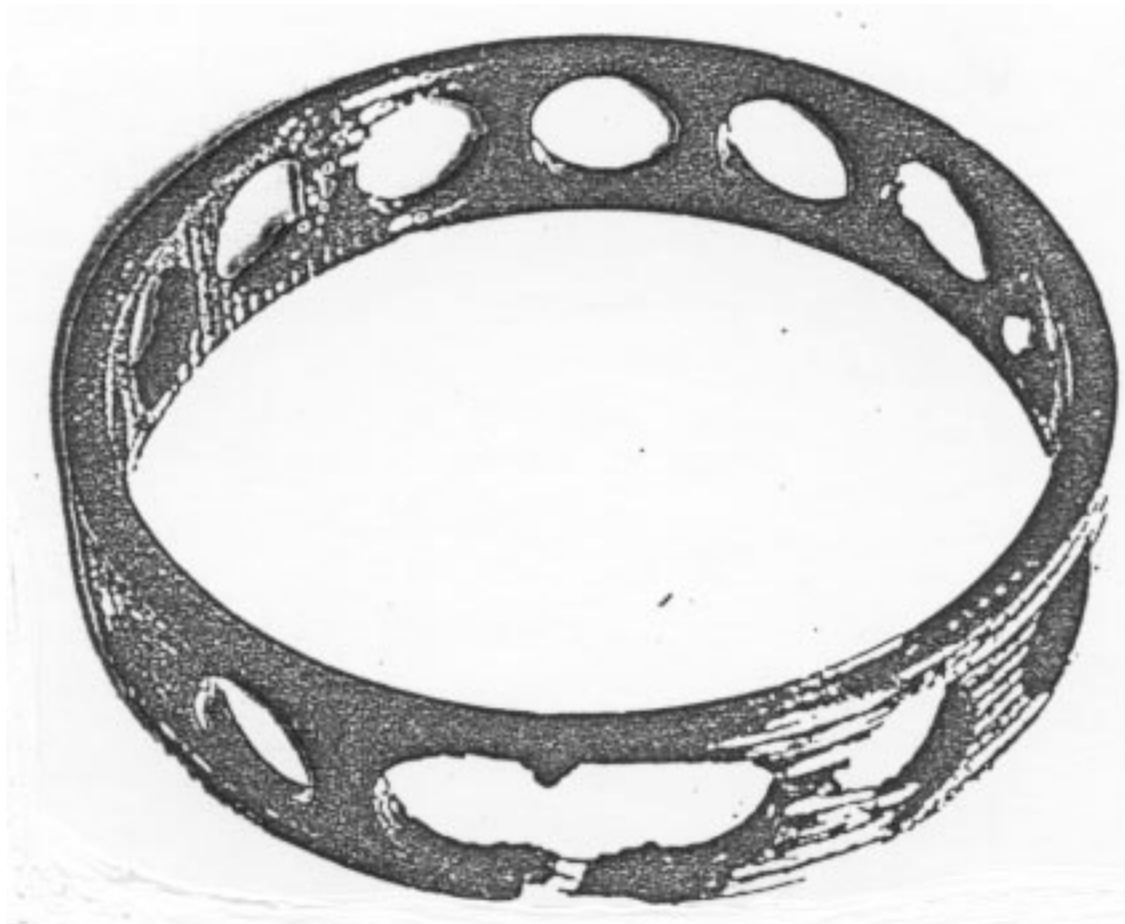
# Frictional Interactions

## Typical rolling element to race traction



# Typical Dynamic Cage Failures

## Cage Damage under Skid Instability



# ADORE Technical Development

## Day 3: Dynamics Concepts & Interaction Models I

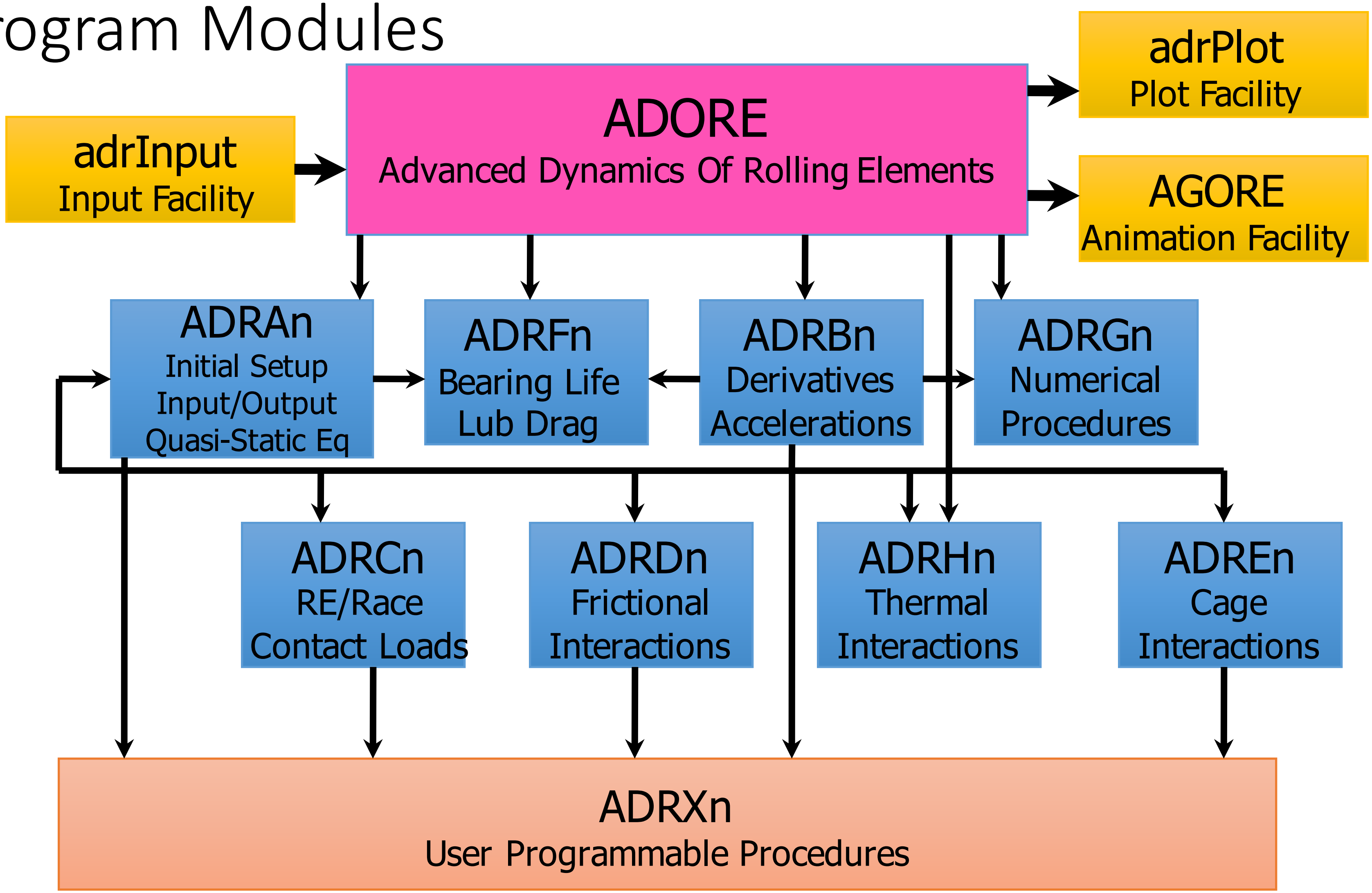
- ADORE base formulation
- Fundamentals in dynamic modeling
- Dimensional organization
- Numerical considerations
  - Short break
- Adore code structure
- Interaction modeling recap
- Rolling element to race interaction – normal load
- ADORE module ADRC1
  - Lunch Break
- Frictional interactions basics
- Rolling element to race interaction – frictional loads
- ADORE module ADRD1
  - Short Break
- Significance of frictional interactions in rolling bearing
- Discussion

# Seminar Outline

- Day 1 – Fundamentals and ADORE overview
- Day 2 – ADORE input/output and user instructions
- Day 3 – Dynamics Concepts & Interaction Models I
- Day 4 – Interaction Models II and Other Codes
- Day 5 – Design Procedures and Examples

# ADORE Overview

## Program Modules



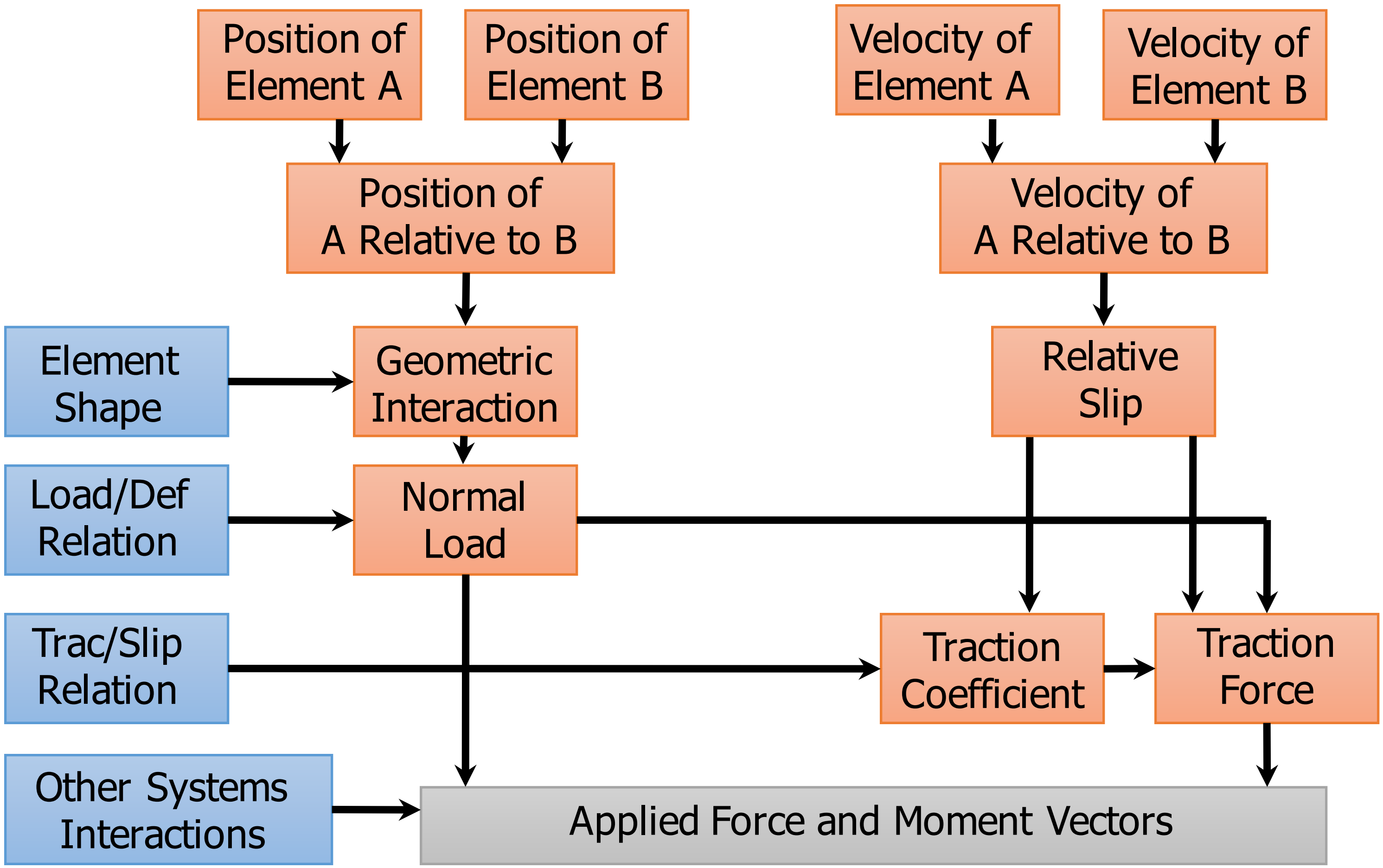
# ADORE Technical Development

## Day 4: Interaction Models II and Other Codes

- Cage pocket interactions
- Handling of rolling element collisions
- Hydrodynamics in cage pockets
- ADORE module ADRE1
    - Short break
- Cage/Race interaction
- Hydrodynamics at cage lands
- ADORE module ADRE2
    - Lunch Break
- Life modeling
- ADORE module ADRF1
- Churning & drag effects
- ADORE module ADRF2
    - Short Break
- Customized modeling examples
- ADORE user code module ADRX1
- Other ADORE code modules ADRB, ADRG and ADRH
- Discussion

# Interaction Modeling

## Generic Approach Recap

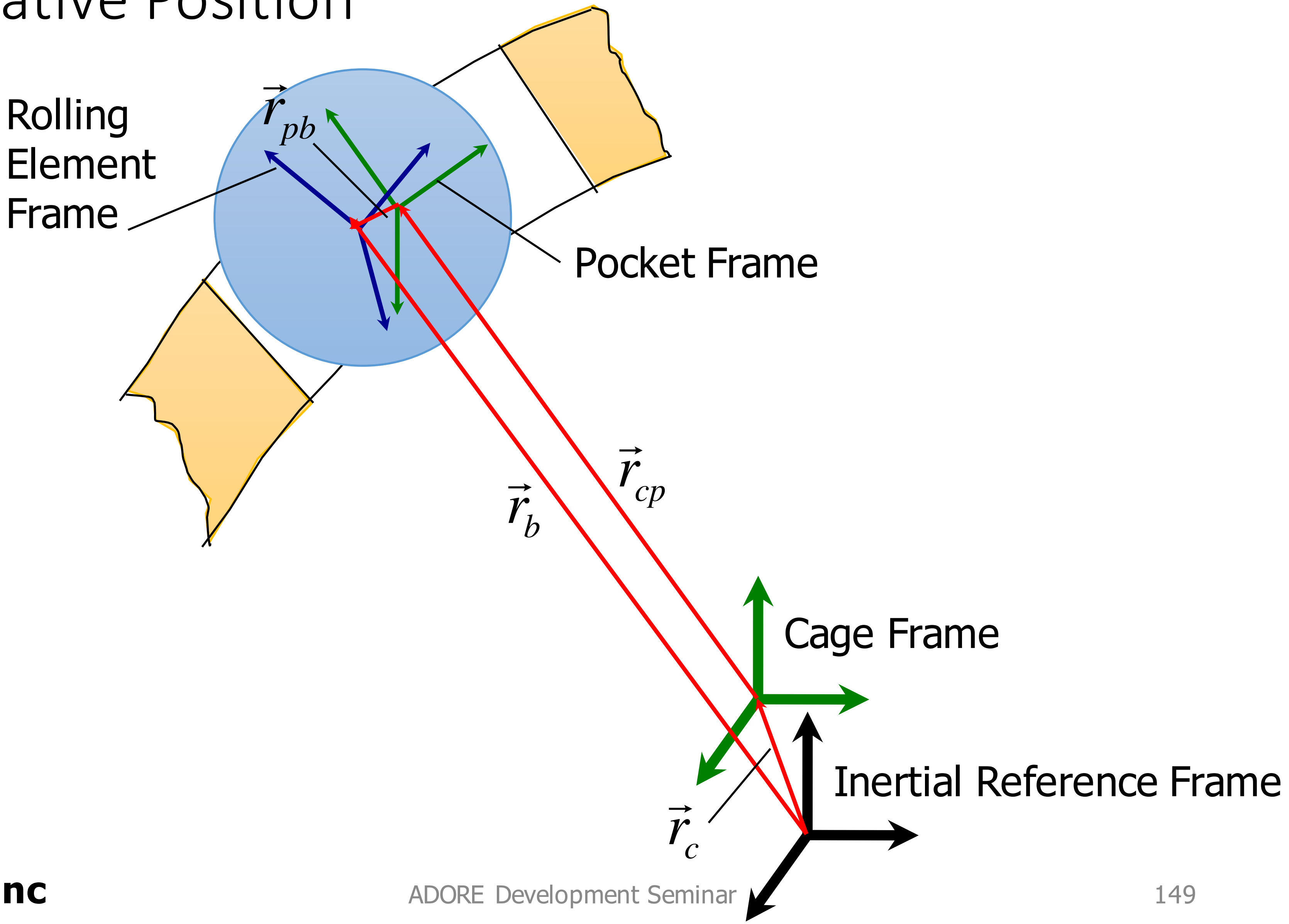


# Interaction Models
## Cage Pocket Contacts

- Locate rolling element relative to cage pocket
- Compute geometric interaction for current geometry
- Compute normal force
- Compute friction force

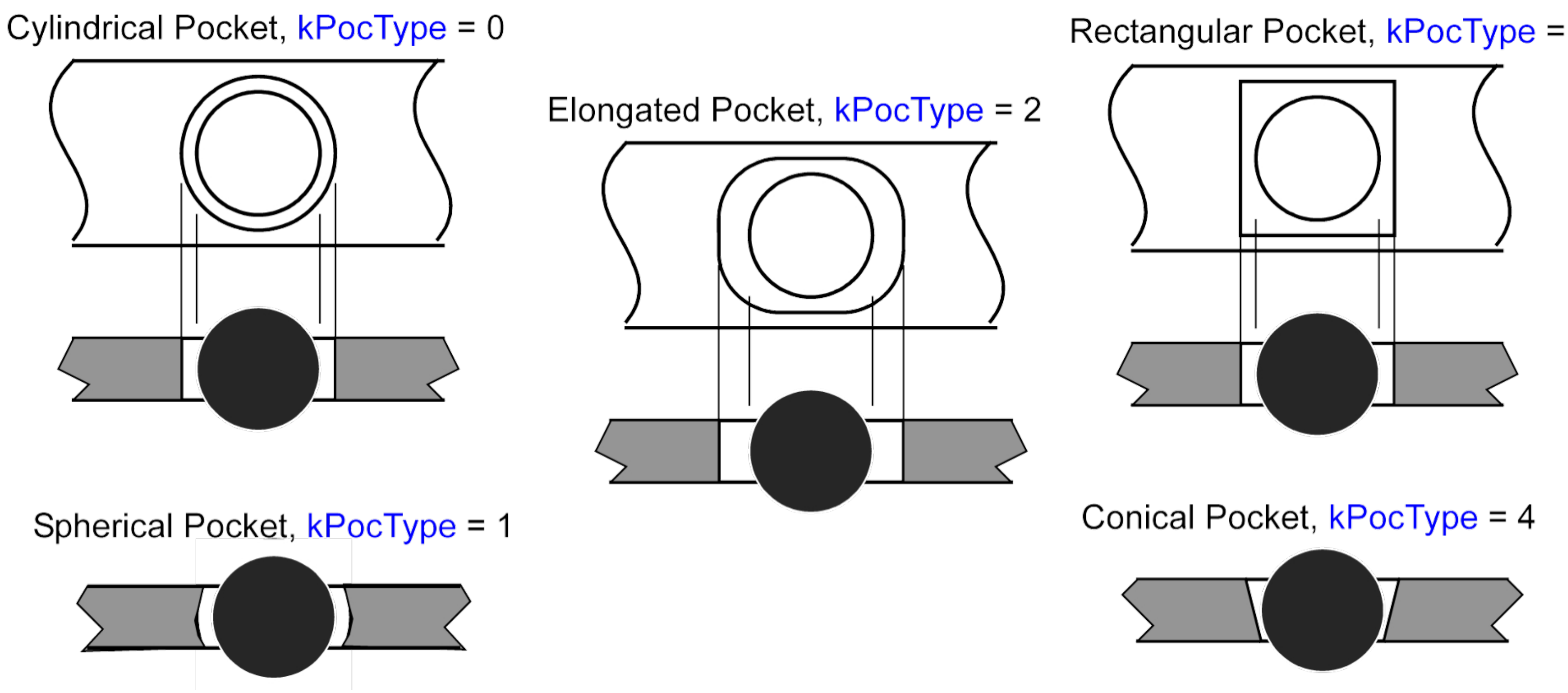
# Rolling Element to Cage Interaction

## Relative Position



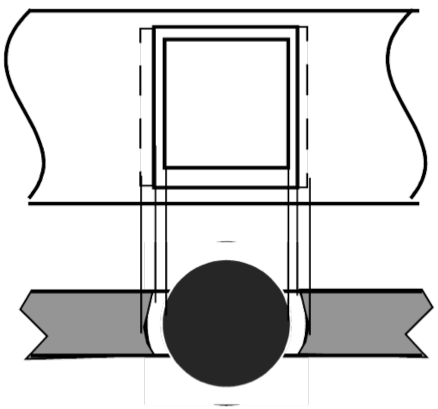
# Rolling Element to Cage Interaction

## Cage Pocket Geometry – Ball Bearings

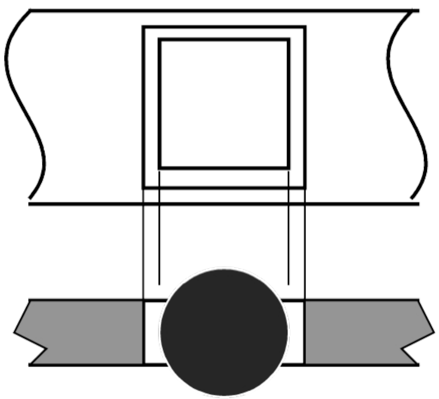


# Rolling Element to Cage Interaction
## Cage Pocket Geometry – Roller Bearings

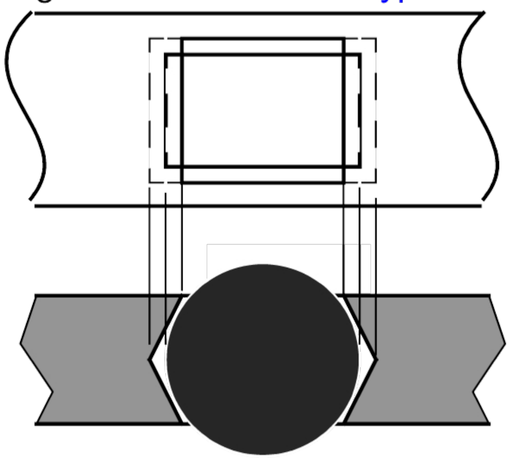
Cylindrical Pocket, kPocType = -1



Rectangular Pocket, kPocType =



Cage Pocket with kPocType = 2



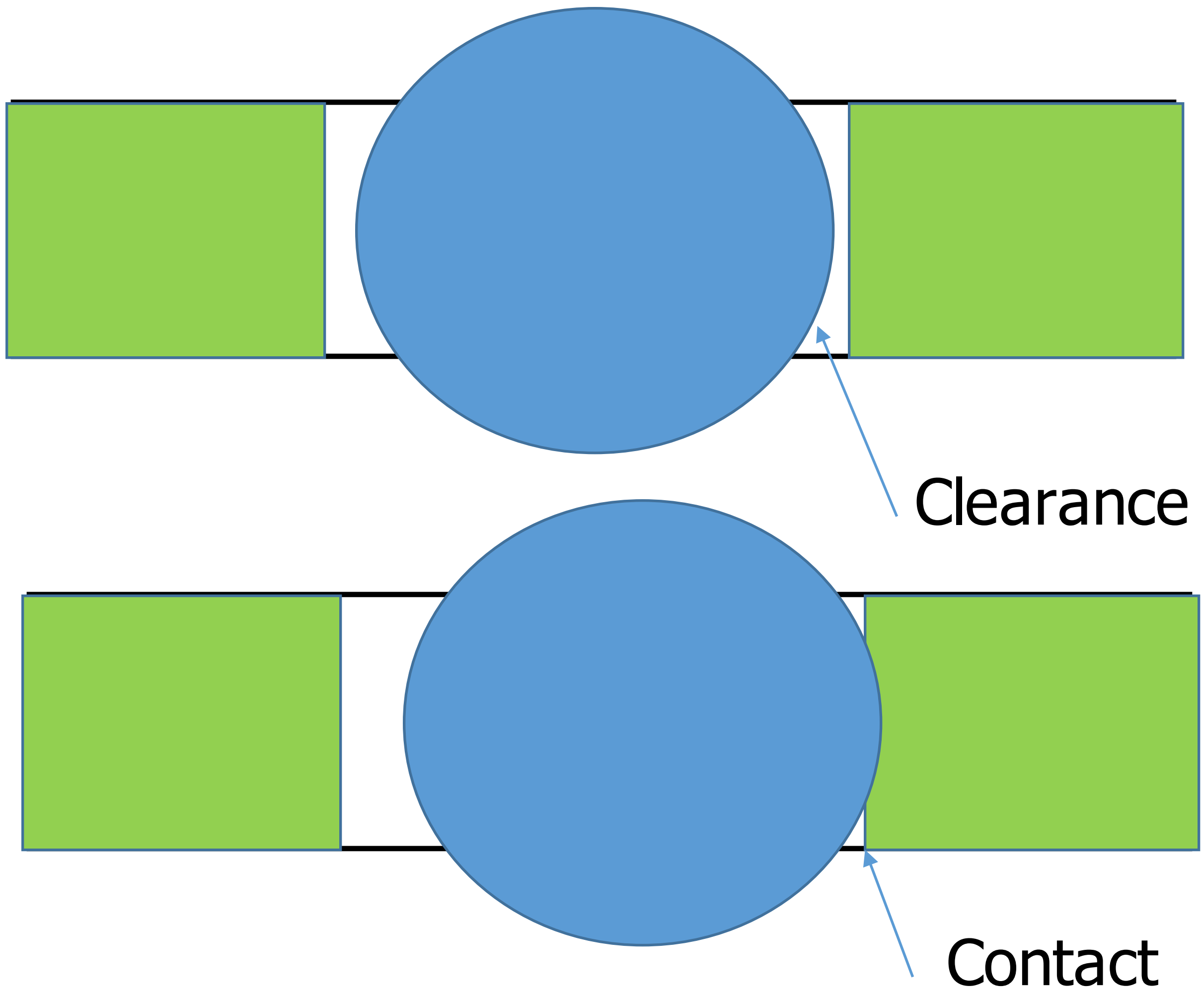
Two pairs of guide surfaces

# Cage Pocket Geometry
## Additional ADORE Options

- Geometrical imperfections
- Arbitrary pocket distribution and orientation

# Rolling Element to Cage Interaction

## Geometric Interaction



# Rolling Element to Cage Interaction
## Normal Force

- Hydrodynamic contact in case of clearance
  - Long journal bearing approximation for roller bearings
  - Short and long journal bearing approximation for ball bearings
  - Data base created upon data setup, interpolation used there after
- Dry contact
  - Classical Hertzian point for line contact
  - Arbitrary user programmable contact stiffness

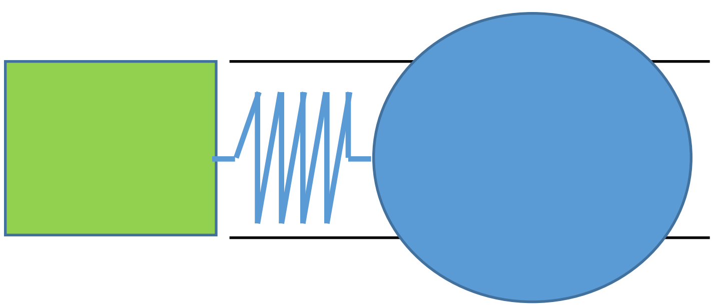
# Rolling Element to Cage Interaction
## Friction Force

- Cage friction is important input for stability
- Normally a high sliding contact, no rolling
- Models used in ADORE
  - Hypothetical traction-slip curve
  - Constant friction coefficient
  - Arbitrary friction-slip slopes
- Realistic values must be validated experimentally

# Rolling Element to Cage Interaction

## Handling of Discontinuities

- Cage pocket forces are highly dynamic
  - Discontinuity upon initiation
- New characteristic frequency
  - Rolling element to cage contact vibration
- Compare current step size with wave length corresponding to cage contact vibration
- Make appropriate adjustment in time step size



$$\omega = \sqrt{\frac{k}{m}}$$

# Rolling Element to Cage Interaction
## ADORE Code Module

- **Code view module ADRE1**

# ADORE Technical Development

## Day 4: Interaction Models II and Other Codes

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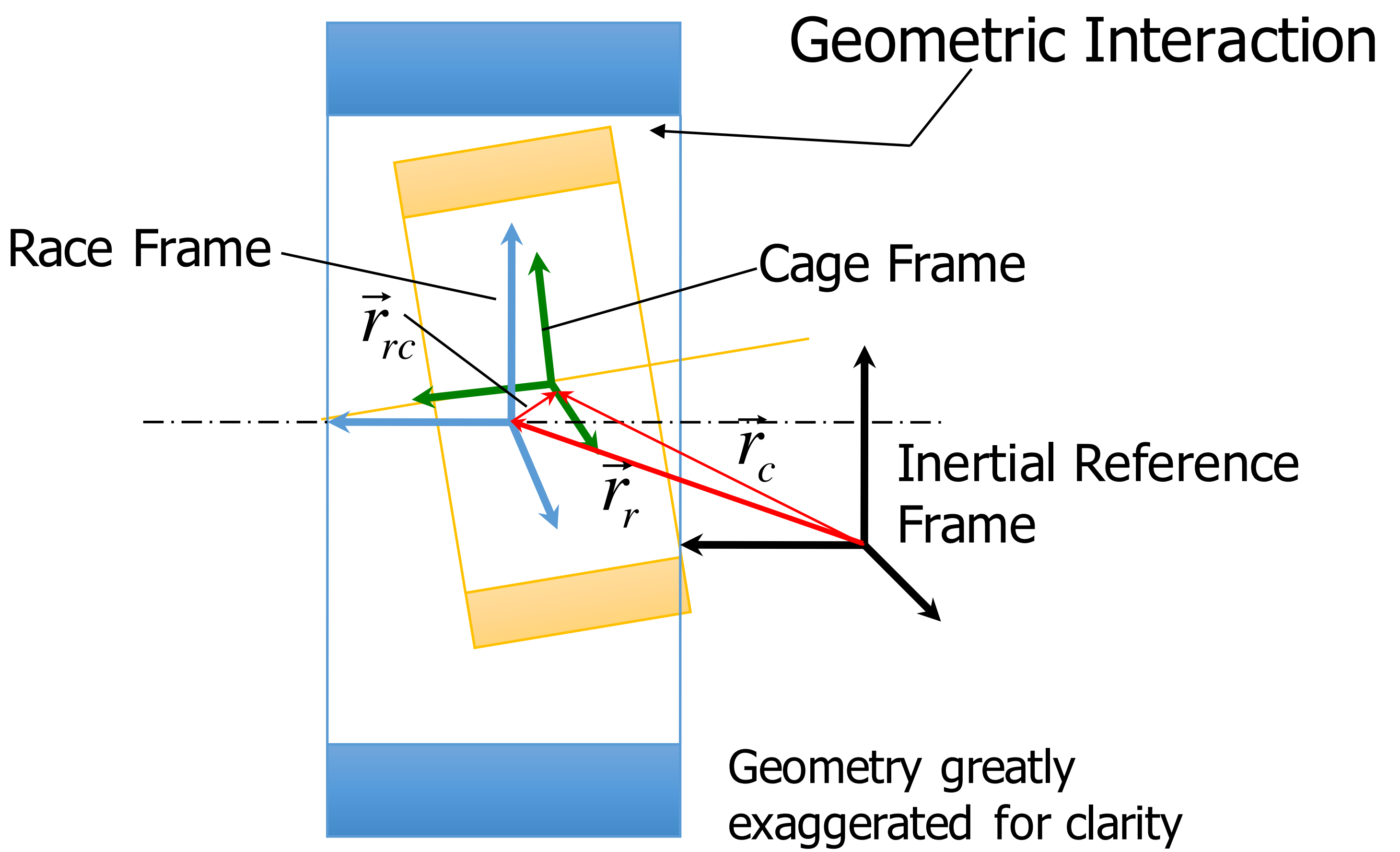
# Interaction Models
## Race/Cage Contacts

- Locate cage relative to race guide land
- Compute geometric interaction for current geometry
- Compute normal force
- Compute friction force

# Cage to Race Interaction

## Relative Position and Geometric Interaction




Geometry greatly exaggerated for clarity

# Race to Cage Interaction ADORE Options

- Arbitrary cage and race land geometries
- Number of guidelands
- Geometrical imperfections
  - Out of roundness of both cage and race surfaces

# Race to Cage Interaction
## Normal Force

- Hydrodynamic contact in case of clearance
  - Short and long journal bearing approximation
  - Data base created upon data setup, interpolation used there after
- Dry contact
  - Classical line contact
  - Arbitrary user programmable contact stiffness

# Race to Cage Interaction
## Friction Force

- Cage friction is important input for stability
- Relatively high sliding contact
- Models used in ADORE
  - Hypothetical traction-slip curve
  - Constant friction coefficient
  - Arbitrary friction-slip slopes
- Realistic values must be validated experimentally

# Race to Cage Interaction
## ADORE Code Module

- **Code view module ADRE2**

# ADORE Technical Development

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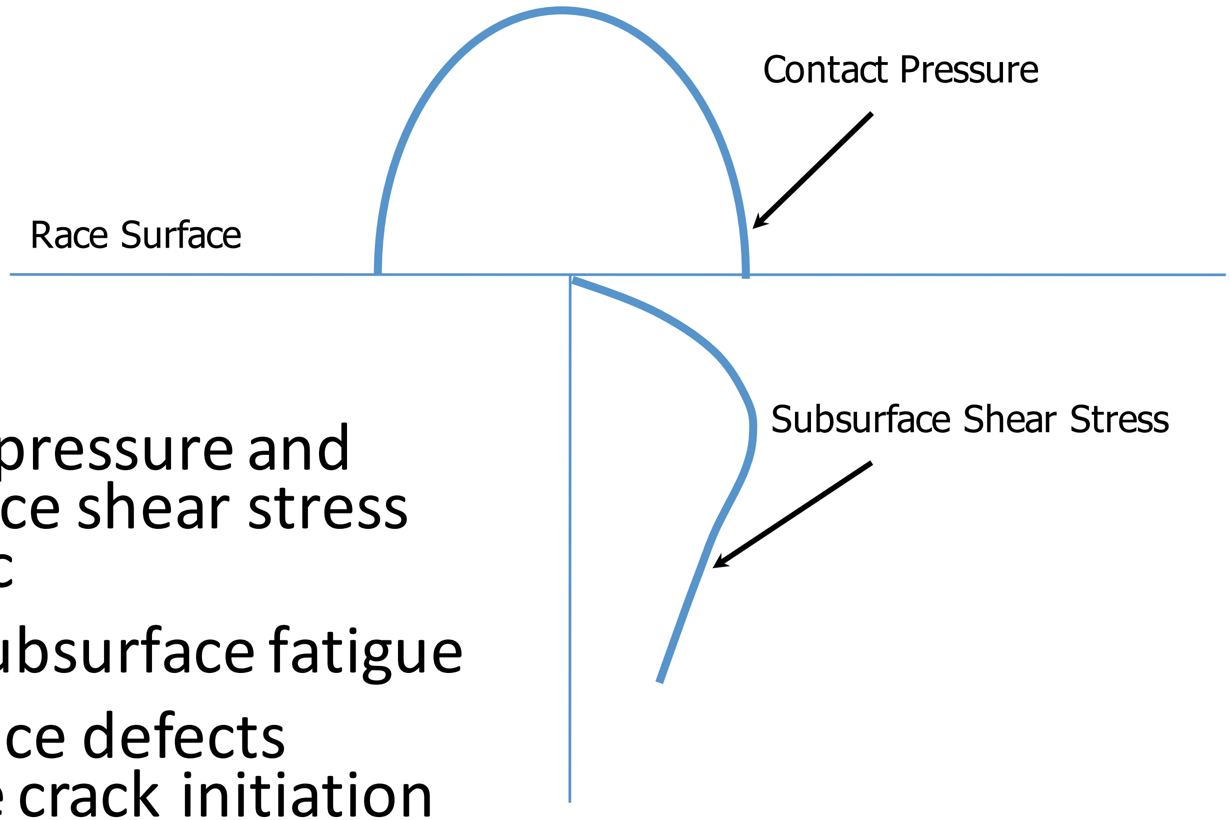
# Bearing Fatigue Life Modeling

## Two Common Approaches

- Simple catalog-type approach
  - Already established life equation as a function of bearing size and operating variables
  - Operational parameters are input in terms of "equivalent" values
  - No analysis of bearing interactions is required
- More rigorous approach based on detailed bearing analysis (**ADORE Approach**)
  - All rolling element-to-race contacts are analyzed
  - Life algorithms are applied to each contact
  - Bearing life is then derived by appropriate summation of individual interactions

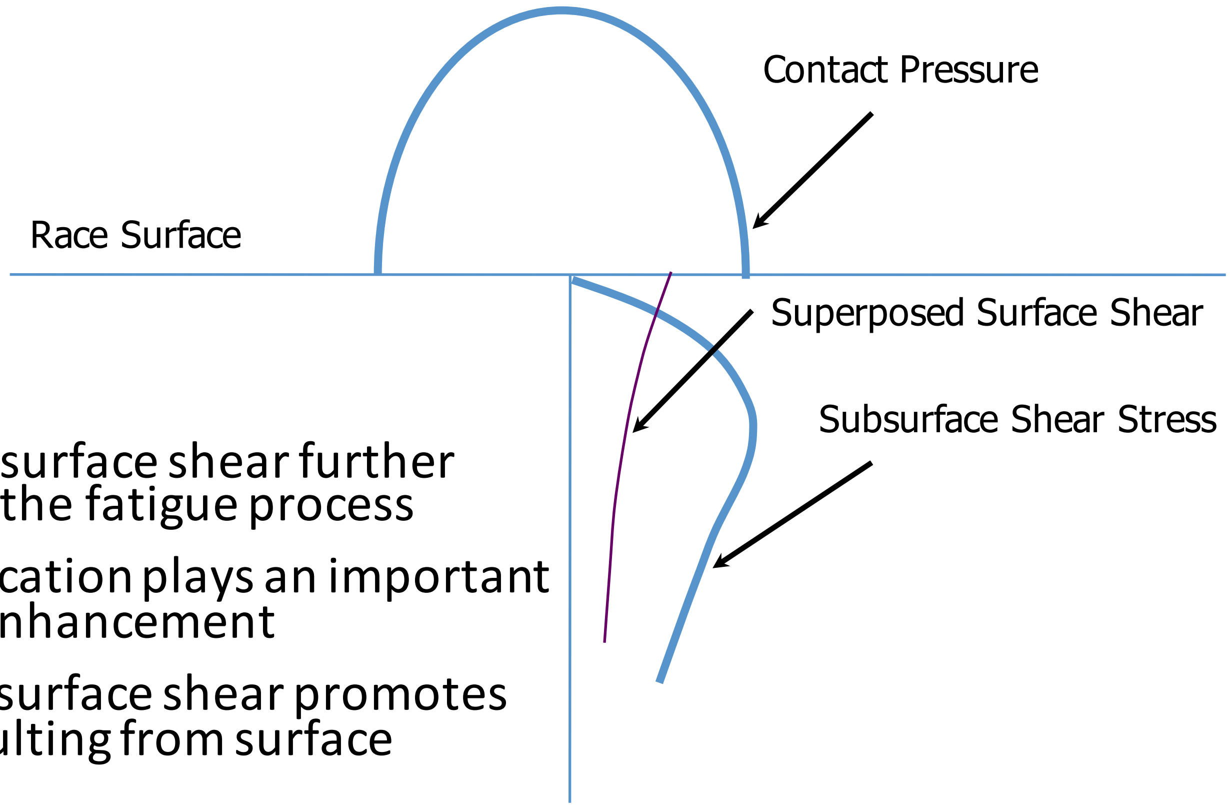
# Fatigue Life Modeling

## Some Fundamentals




- Contact pressure and subsurface shear stress are cyclic
- Hence subsurface fatigue
- Subsurface defects promote crack initiation

# Fatigue Life Modeling
## Some Fundamentals



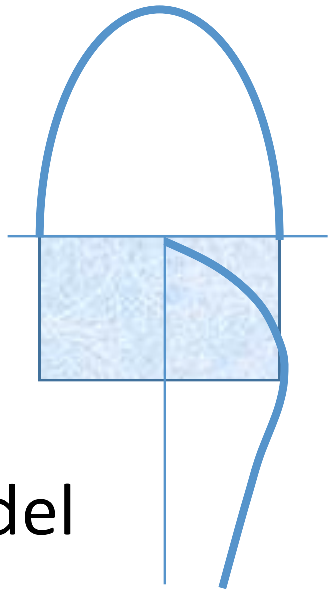

- Addition of surface shear further accelerates the fatigue process
- Hence lubrication plays an important role in life enhancement
- In addition surface shear promotes failures resulting from surface defects

# Fatigue Life Modeling
## Base Life Definition

- Generally known as $L_{10}$ life, implying 10% failure or 90% survival probability
- Base life is strictly a consequence of cyclic subsurface shear stress

# Fatigue Life Modeling

## Base models



- Weibull postulation

$$\ln\frac{1}{S} \sim \int_V f(\sigma)dV$$

- Commonly used Lundberg-Palmgren model

$$\left(\frac{1}{N_{10}}\right)^m = K_{LP}\frac{\tau_o^c V_o}{z_o^h}$$

- Recently Developed Gupta-Zaretsky model

$$\left(\frac{1}{N_{10}}\right)^m = K_{GZ}\tau_m^{cm}V_m$$

# Fatigue Life Modeling
## References

Gupta, P.K., Oswald, F.B. and Zaretsky, E.V., 2012, "Comparison of models for rolling bearing dynamic capacity and life", STLE Tribology Transactions, Vol 58, 2015, 1039-1053

Gupta, P.K. and Zaretsky, E.V., "Generalized Fatigue Life Models for Rolling Bearings", to be published, STLE Transactions

# Bearing Life Modeling

## Life Modification Factors

- Material matrix factor
- Bulk defect factor
- Surface defect factor
- Lubrication factor
- Load distribution factor


Gupta, P.K. & Tallian, T.E., "Rolling Bearing Life Prediction – Correction for Materials and Operating Conditions – Part III: Impementation in Bearing Computer Codes", ASME Journal of Tribology, Vol 112, pp 23-26, 1990

Tallian, T.E., "Data Fitted Bearing Life Prediction Model for Variable Operating Conditions", STLE Tribology Transactions, Vol 42, pp 241-249, 1999.

Zaretsky, E.V., 1992, *STLE Life Factors for Rolling Bearings*, STLE Park Ridge, IL.

# Bearing Modeling
## Computational Outline

- Solve equilibrium equations
- Compute load and lubricant film thickness at each contact
- Compute both basic life and life, as modified by various life modification factors at each contact
- Compute life for each raceway and rolling elements
- Perform statistical summation to compute life for the entire bearing

# Bearing Modeling
## ADORE Code Module – Fatigue Life

- **Code view module ADRF1**

# Churning and Drag Modeling
## Problem Significance

- Bearing cavity filled with fluid
- Lubricant/Air mixture for lubricated bearings
- Cryogenic fluid in space shuttle turbo pump applications
- Bearing elements have to move through the fluid
- Resulting drag forces and churning moments are imposed on the bearing elements
- Resulting additional heat generation affects both fluid properties and bearing operation

# Churning and Drag Modeling
## Some Fundamentals

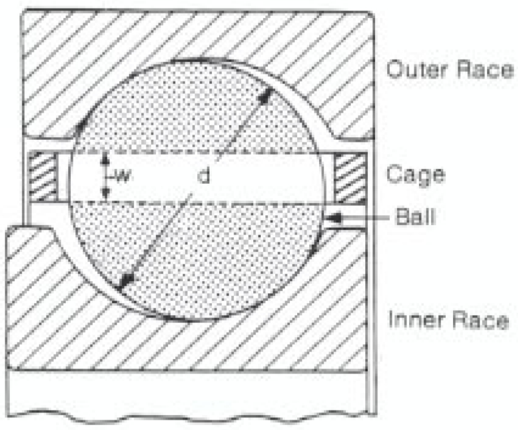
- Classical laminar and turbulent flow theories'
- Drag forces on rolling elements
- Churning and drag on rolling element surfaces
- Churning on cage surfaces

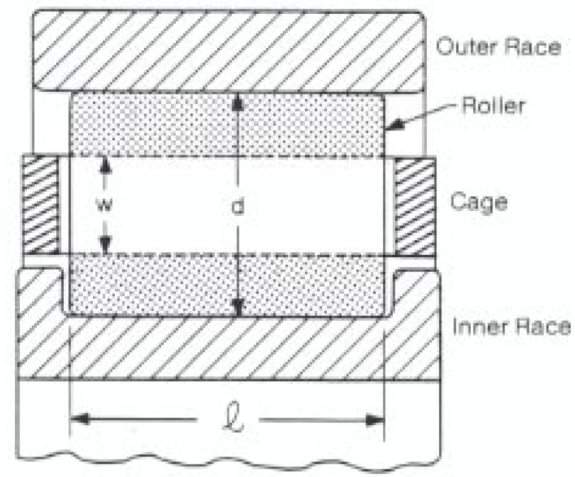
Schlichtig, H., *Boundary Layer Theory*, McGraw Hill, 1968, 15-19, 93-99, 606-608

Rumbarger, J.H., Filetti, G.G. and Gubernick, D., "Gas turbine engine main shaft roller bearing system analysis", ASME Journal of Lubrication Technology, vol 95, 401-416, 1973.

Gupta, P.,K. *Advanced Dynamics of Rolling Elements*, Spriger-Verlag, 1984.

# Churning and Drag Modeling
## Drag Forces on Rolling Elements



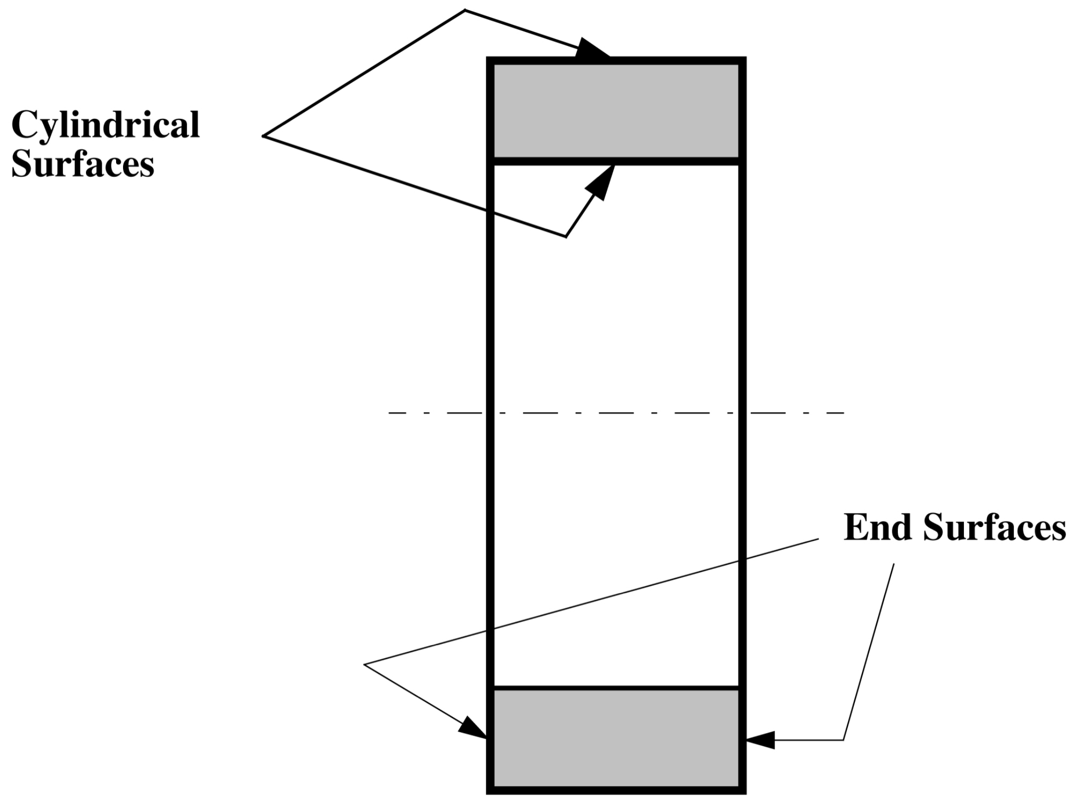

- Drag force, $$D = \frac{1}{2} C_D \rho V^2 A$$

- Drag coefficient is tabulated as a function of Reynolds number, $$R_e = \frac{\rho V d}{\mu}$$

# Churning and Drag Modeling

## Applicable cage surfaces

- Cylindrical surfaces
- End surfaces



# Churning and Drag Modeling
## Churning Moments on Cylindrical Surfaces

- Churning moment, $M_e = \tau A r = \left(\frac{1}{2} f \rho U^2\right) A r$

Friction factor f depends on flow conditions

- Vortex turbulent flow $\frac{f}{f_L} = 1.3 \left(\frac{T_a}{41}\right)^{0.539474}$

  Taylor's number $T_a = \frac{\rho r \omega c}{\mu}\left(\sqrt{\frac{c}{r}}\right) > 41$

- Coutte turbulent flow $\frac{f}{f_L} = 3.0 \left(\frac{R_e}{25000}\right)^{0.85596}$

  Reynold's number $R_e = \frac{\rho r \omega c}{\mu} > 25000$

# Churning and Drag Modeling
## Churning Moments on Cylindrical Surfaces

- Laminar friction factor

$$f_L = \frac{16}{R_e} \qquad R_e < 25000 \; or \; T_a < 41$$

Flow on cage surfaces is assumed to be Couette,
While that on roller surfaces is approximated as
Vortex

# Churning and Drag Modeling

## Churning Moments on end Surfaces

- Churning moment, $M_e = \frac{1}{2}\rho\omega^2 r^5 C_n$
- Laminar flow, Reynold's number $R_e = \frac{\rho\omega r^2}{\mu} < 300{,}000$

$$C_n = \frac{3.87}{R_e^{0.50}} \quad r^5 = r_{out}\left(r_{out}^4 - r_{in}^4\right)$$

- Turbulent flow, Reynold's number $R_e = \frac{\rho\omega r^2}{\mu} > 300{,}000$

$$C_n = \frac{0.146}{R_e^{0.20}} \quad r^5 = r_{out}^{0.40}\left(r_{out}^{4.60} - r_{in}^{4.60}\right)$$

- Effective radius for Reynold's number

$$r = r_{out}$$

This formulation is also used for balls on a surface projected on a plane normal to the angular velocity vector

# Bearing Modeling
## ADORE Code Module – Churning & Drag

- **Code view module ADRF2**

# ADORE Technical Development

## Day 4: Interaction Models II and Other Codes

- Cage pocket interactions
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# Modeling of Specialized Effects
## ADORE User Programmable Procedures

- Certain complex operating environment requires that certain time-varying behavior be programmed in lieu of operating conditions specified by just a few variables
- Often operating conditions are determined by other modeling tools which are intricately coupled with bearing behavior
- Some of the classical models used in ADORE are not realistic and their replacement with more complex model is required for acceptable performance modeling

# ADORE User Programmable Procedures
## Code Group ADRX

- ADRX0 - User materials data base
- ADRX1 - Applied load and speed variations
- ADRX2 - Roller/flange spring rate
- ADRX3 - Rolling element/cage spring rate
- ADRX4 - Race/cage spring rate
- ADRX5 - Roller geometry
- ADRX6 - Race geometry
- ADRX7 - Arbitrary traction/slip relation for rolling element/race contacts
- ADRX8 - Arbitrary geometrical imperfections -rolling elements/cage
- ADRX9 - User output in data file SOL9

# ADORE User Programmable Procedures

## Typical Structure

- Input data
- Initial computations
- Time-varying computations
- Any output documentation
- **Source code view ADRX1**

# ADORE User Programmable Procedures
## Model Development & ADORE Interface

- Test area in ADORE
- **ADORE source code view**

# ADORE User Programmable Procedures

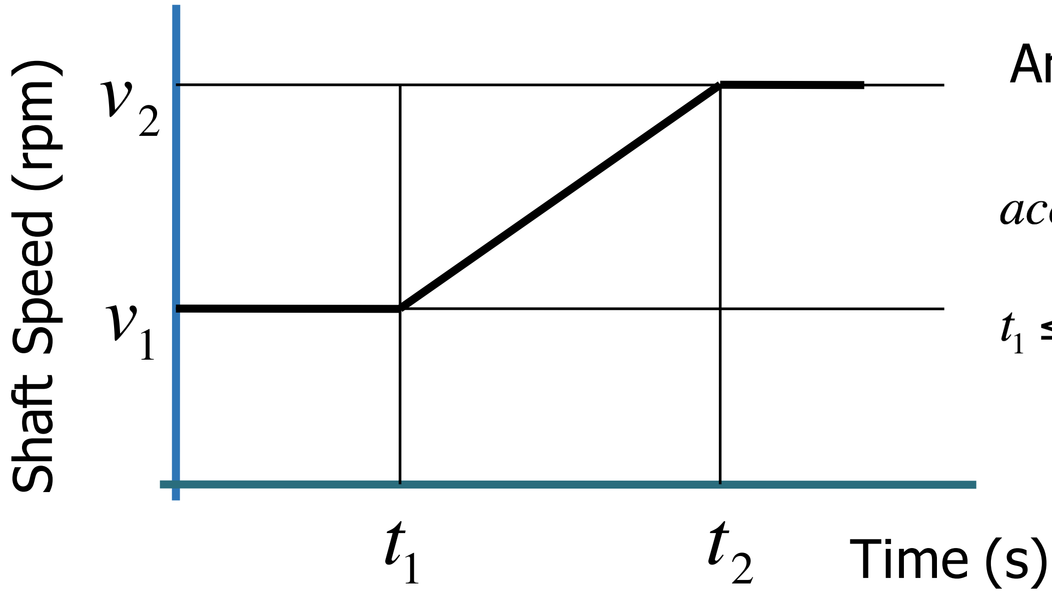
## Some Examples

- Time variation in speed
  - Accelerate from low to high speed in given time
- Vibrational loading
  - Outer race subject to sinusoidal vibration

# ADORE User Programmable Procedures

## Example 1: Speed Variation

- Accelerate from low to high speed in given time




Angular Acceleration

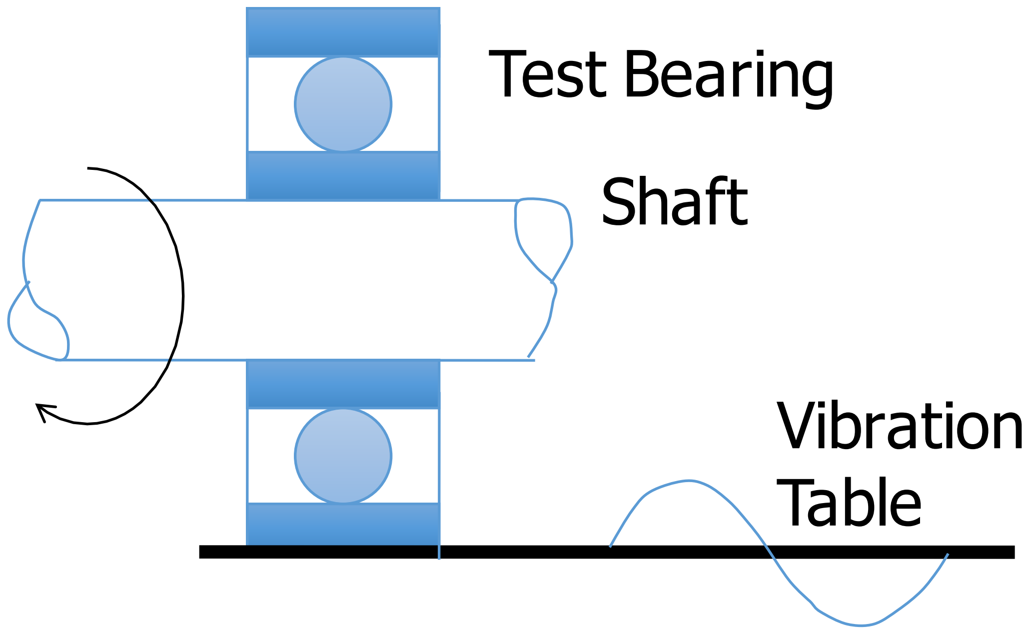
$$acc = \frac{rpm2 - rpm1}{t2 - t1} = \frac{v_2 - v_1}{t_2 - t_1}$$

$$t_1 \le t \le t_2$$

- Code view ADRXEx1

# ADORE User Programmable Procedures
## Example 2: Vibrational Loading

- Outer race subjected to sinusoidal vibration




*Position* :

$$A = A_o \sin \omega t$$

*Velocity* :

$$\dot{A} = A_o \omega \cos \omega t$$

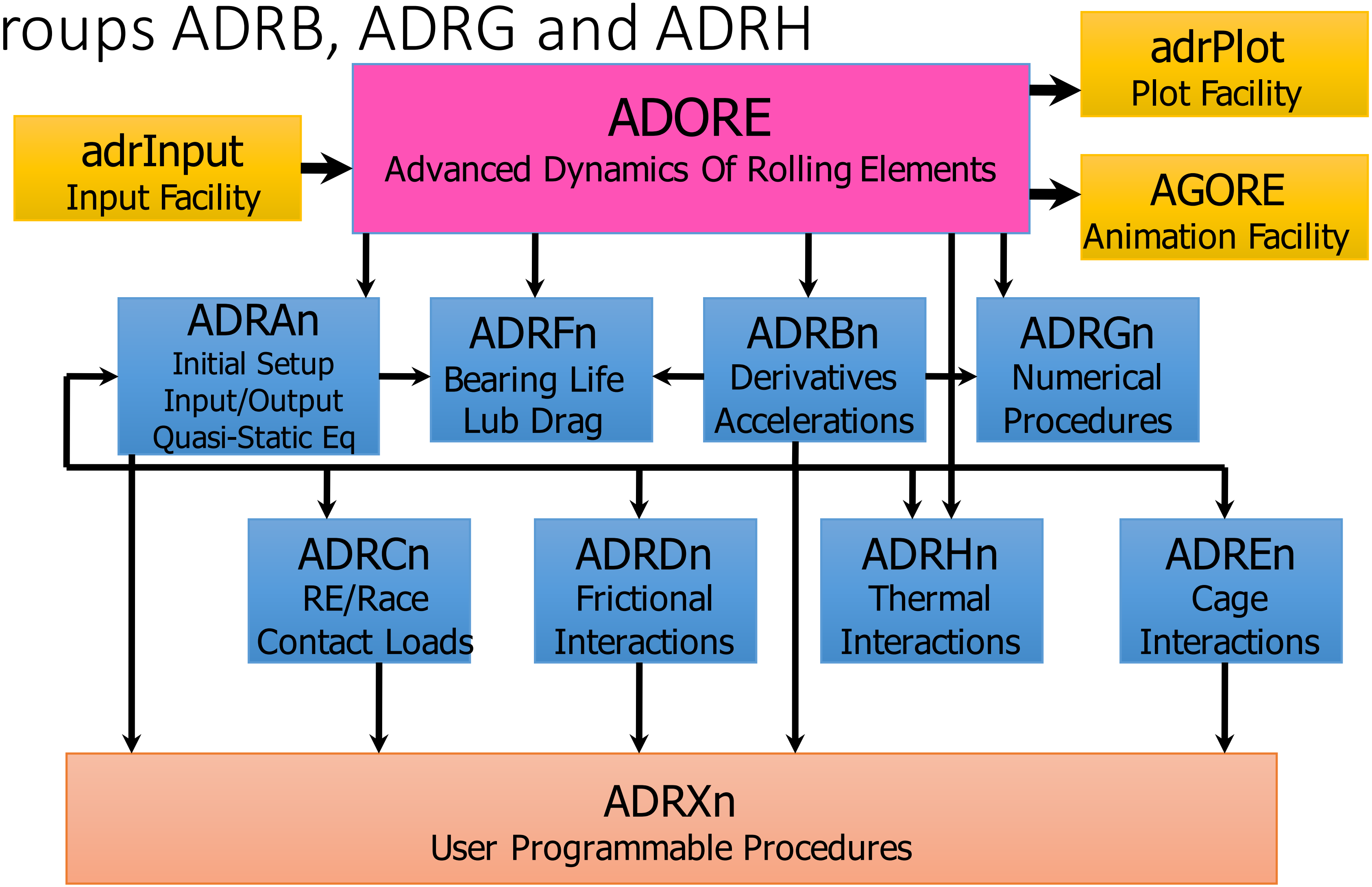
*Acceleration* :

$$\ddot{A} = -A_o \omega^2 \sin \omega t$$

- **Code view ADREx2**

# ADORE Overview

## Groups ADRB, ADRG and ADRH



# Other ADORE Code Modules

## Groups B, G and H

- Group B: Derivative routine – calls all other procedures to compute accelerations
- Group G: Mathematical procedures
- Group H: Thermal interactions
  - Integration of mechanical, geometrical and thermal environments
  - Presently under more extensive development

# ADORE Technical Development

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# ADORE Development

## Day 5: Design Procedures and Examples

- Bearing design procedures
- Stability diagnosis
- Examples
  - Short Break
- Seminar recap
- User examples – direct experience with ADORE
  - Lunch Break
- User Examples continued
- General Discussion

# Bearing Design Optimization
## Parametric Performance Evaluation

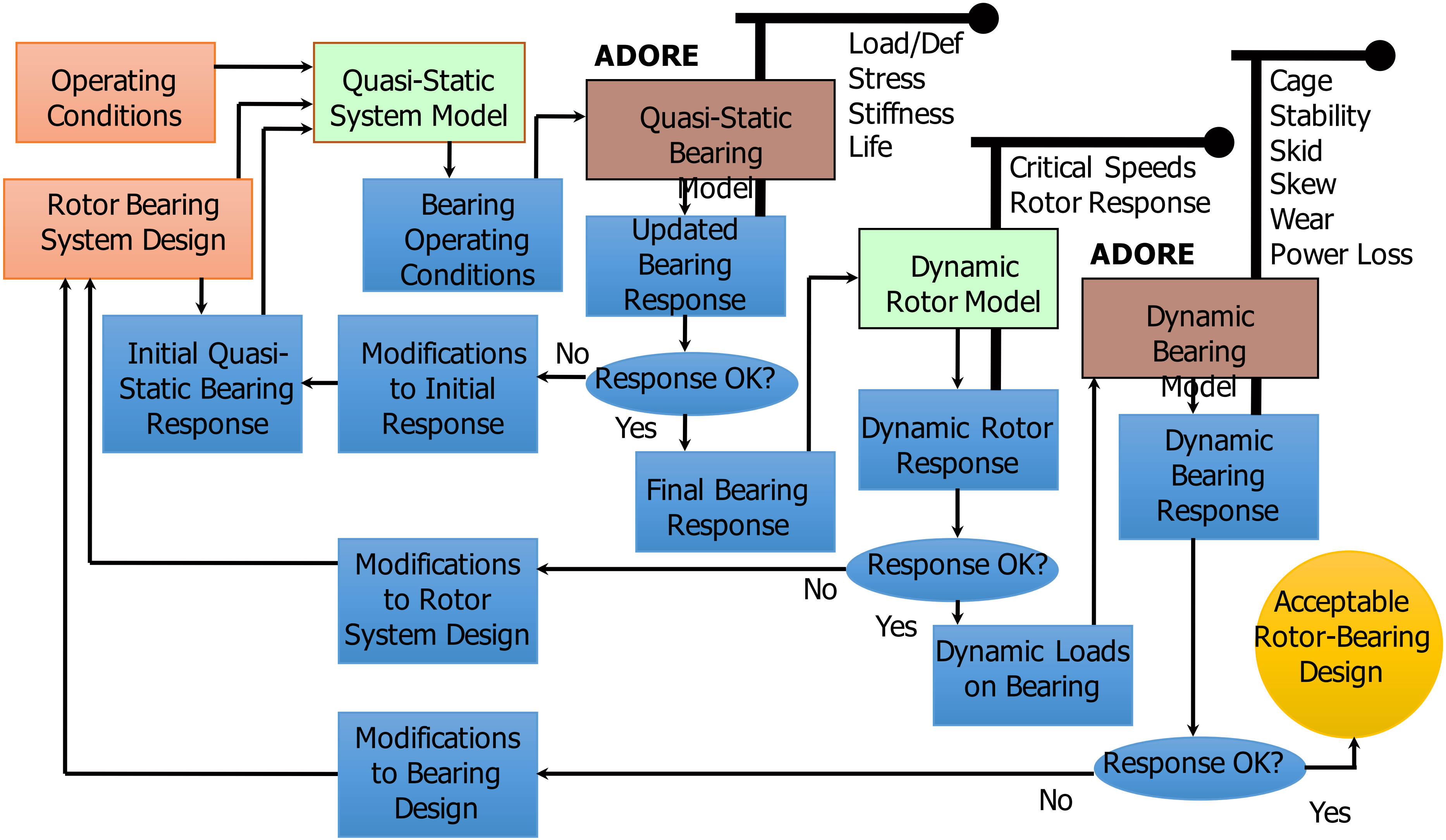
- Bearing life
- Power loss
- Wear
- Stability
- Dynamic variations

# Practical Design Development
## Typical Requirements

- Bearing envelope
- Operating environment
- Life requirements
- Stiffness and rotor response
- Acceptable dynamic behavior

# Practical Design Development

## Schematic Design Optimization Procedure



# Performance Diagnosis
## Broad Failure Classes

- Cumulative failures
  - Bearing fatigue
  - Wear
- Sudden failures
  - Triggered by some type of instability
  - Sudden change in bearing motion
  - Unbounded interactions
  - Critical geometric parameter encountered as a result of wear or thermal issues
  - Thermal ”take off”

# Dynamic Performance Modeling
## Significant Performance Parameters

- Rolling element of race traction
- Cage friction
- Cage to race guide clearance
- Pocket clearance

# Dynamic Performance Modeling

## What is Instability?

- Irregular motion of element element
  - Erratic torque variations
  - Erratic cage whirl
  - Skidding
  - Skewing of rollers
- Interaction levels
  - Bounded
  - Unbounded
    - Eminent failures

# Significant Dynamic Performance Parameter - Time-Averaged Wear Rate

- Archard's wear equation

$$W = K\frac{QV}{H}$$

- Time-varying wear rate

$$W(t) = K\frac{Q(t)V(t)}{H}$$

- Time-averaged wear rate

$$\overline{W} = \frac{1}{T}\int_0^T W(t)dt = \frac{K}{TH}\int_0^T Q(t)V(t)dt$$

- Practical significance
  - Average wear rate and Q and V are bounded
  - Stability indicator when Q and V are unbounded

# Dynamic Performance Examples

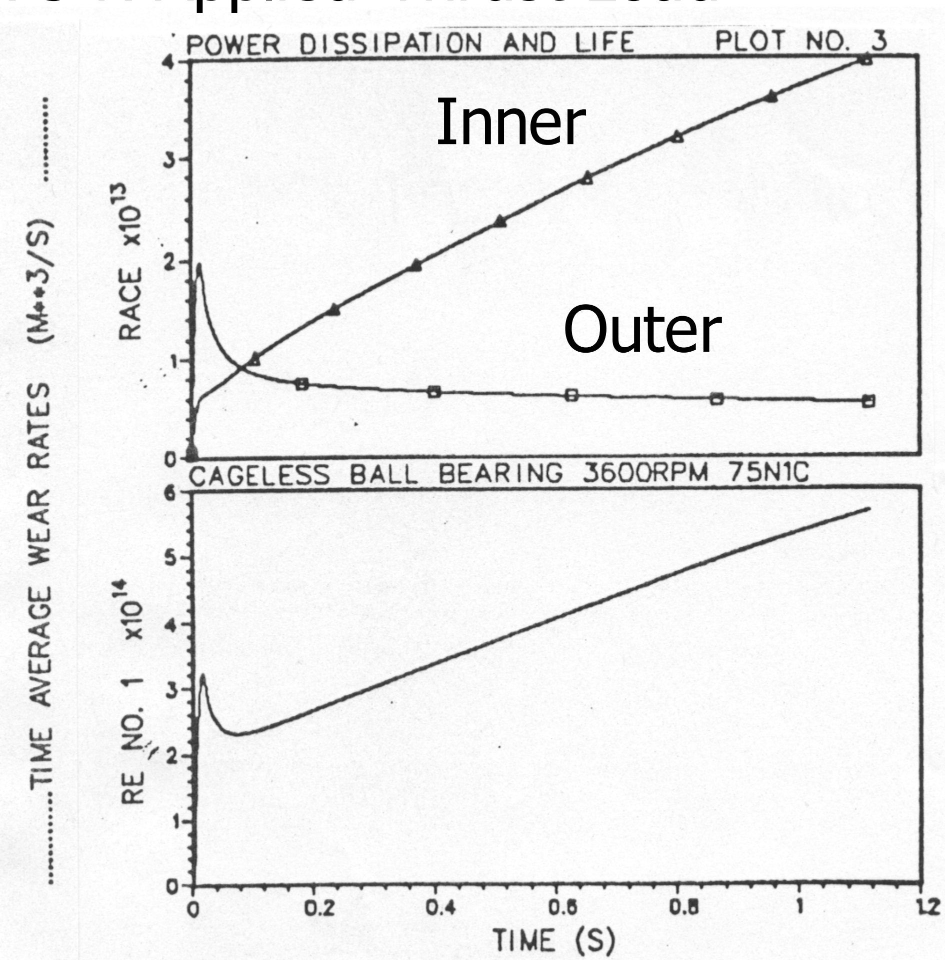
## Typical Instabilities

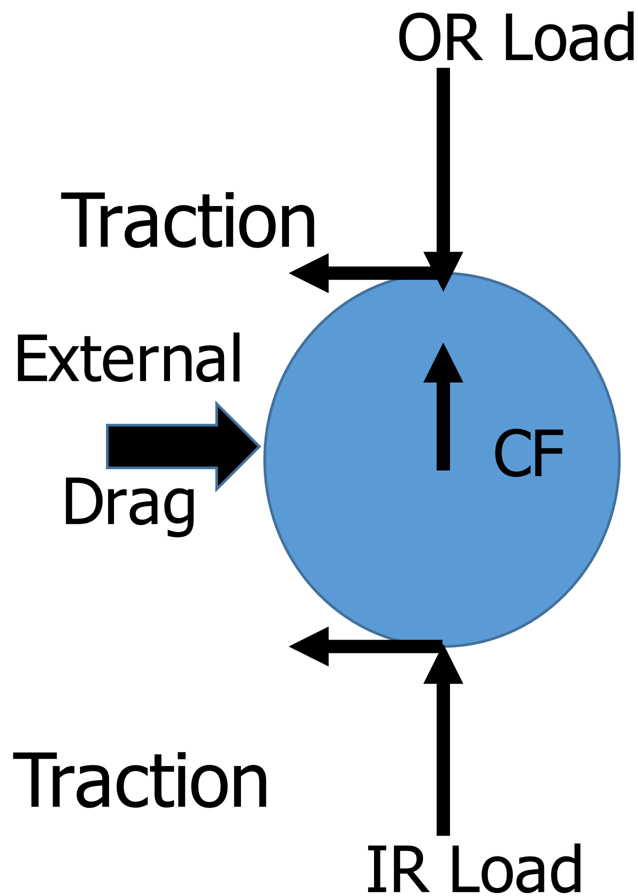
- Rolling element skid
  - Rolling element to race traction inadequate to support other applied forces in orbital direction
- Unbounded cage whirl
  - Mechanical interactions progressively increase with time leading to cage failure

# ADORE Examples

## Rolling Element Skid Instability

75 N Applied Thrust Load

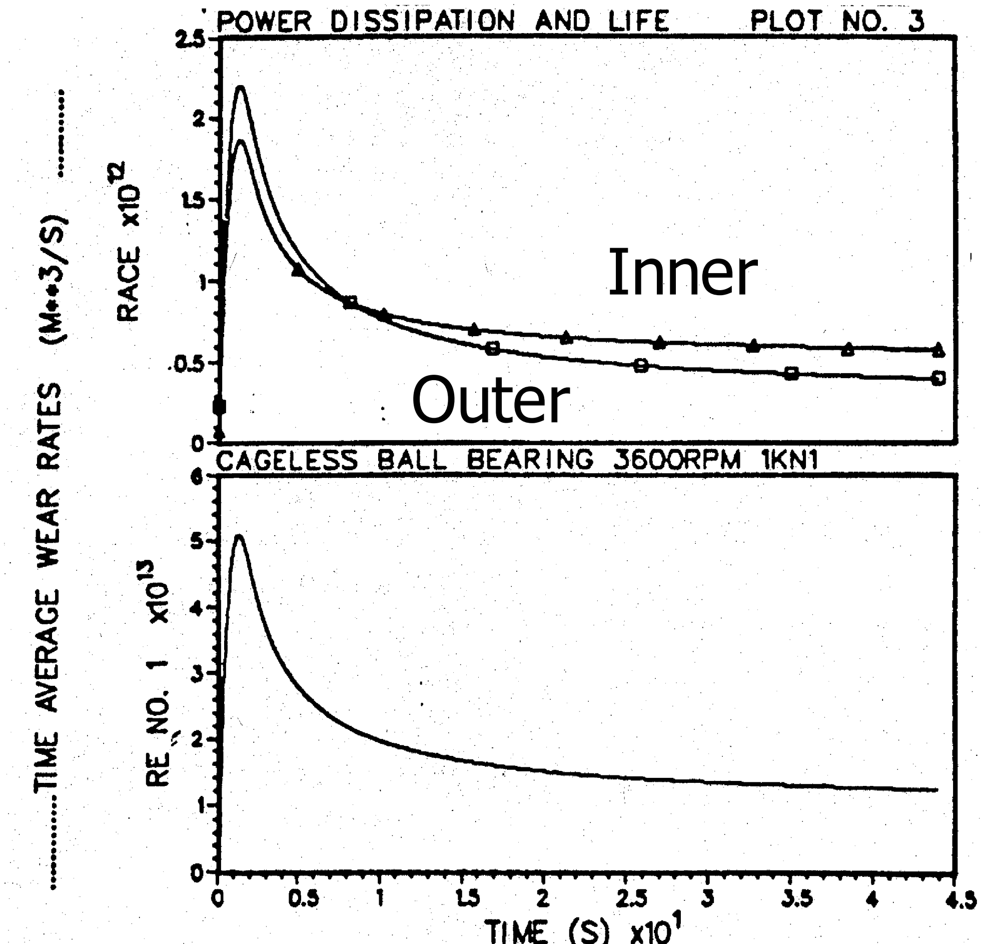


# ADORE Examples

## Rolling Element Skid –Stable Behavior

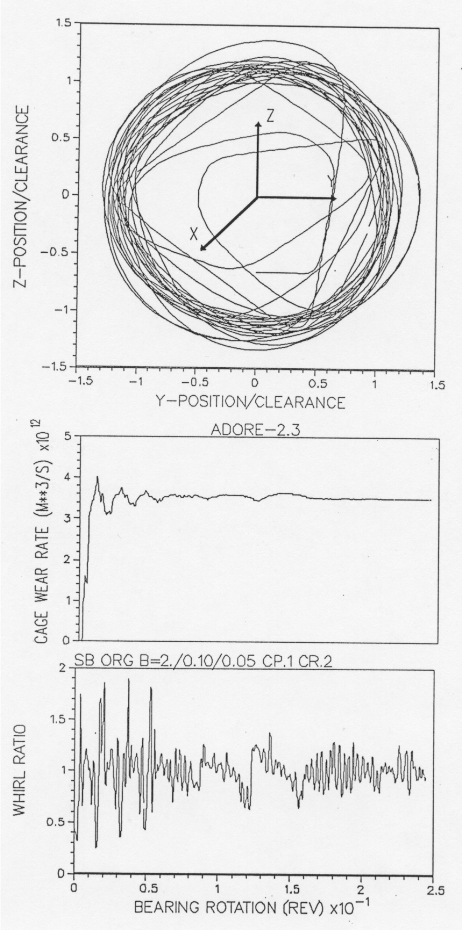
## 1,000 N Applied Thrust Load



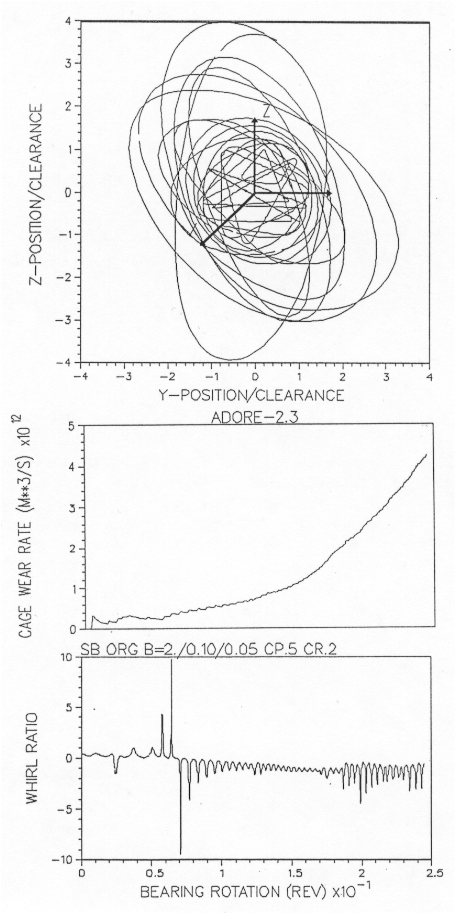
# ADORE Examples

## Cage Whirl Instability with Increasing Pocket Clearance

Pocket Clearance = 0.10 mm




Pocket Clearance = 0.50 mm



# ADORE Development

## Day 5: Design Procedures and Examples

- Bearing design procedures
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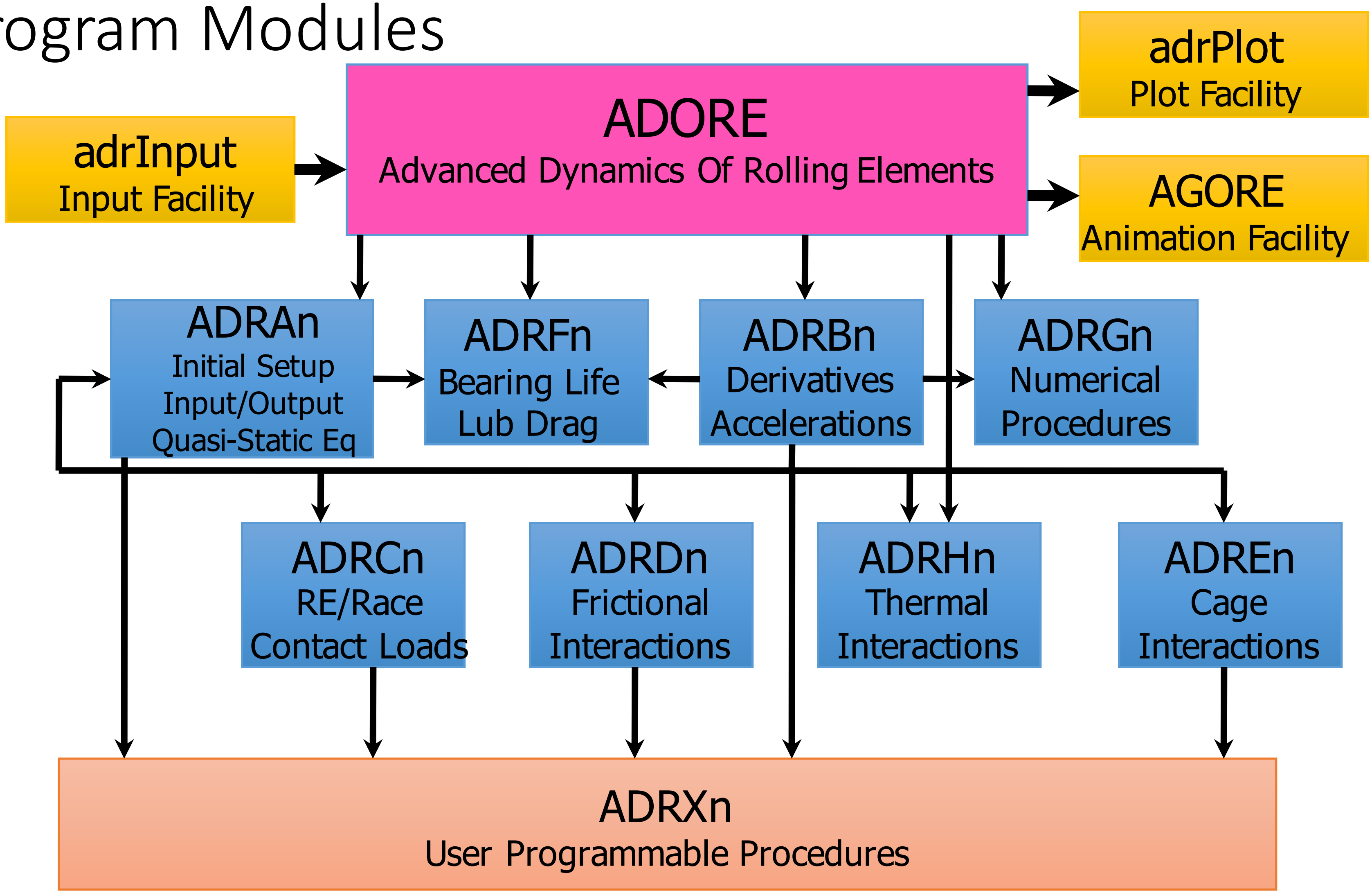
# ADORE Overview

## Program Modules



# ADORE Development

## Day 5: Design Procedures and Examples

- Bearing design procedures
- Stability diagnosis
- Examples
  - Short Break
- Seminar recap
- User examples – direct experience with ADORE
  - Lunch Break
- User Examples continued
- General Discussion