ADORE

Advanced Dynamics Of Rolling Elements Overview

Dr. Pradeep K. Gupta
PKG Inc
Phone: 518-383-1167
guptap@PradeepKGuptaInc.com

ADORE Overview

- Introduction
- Program Overview
- Experimental Validation
- Significant Parameters in Dynamic Modeling
- Examples

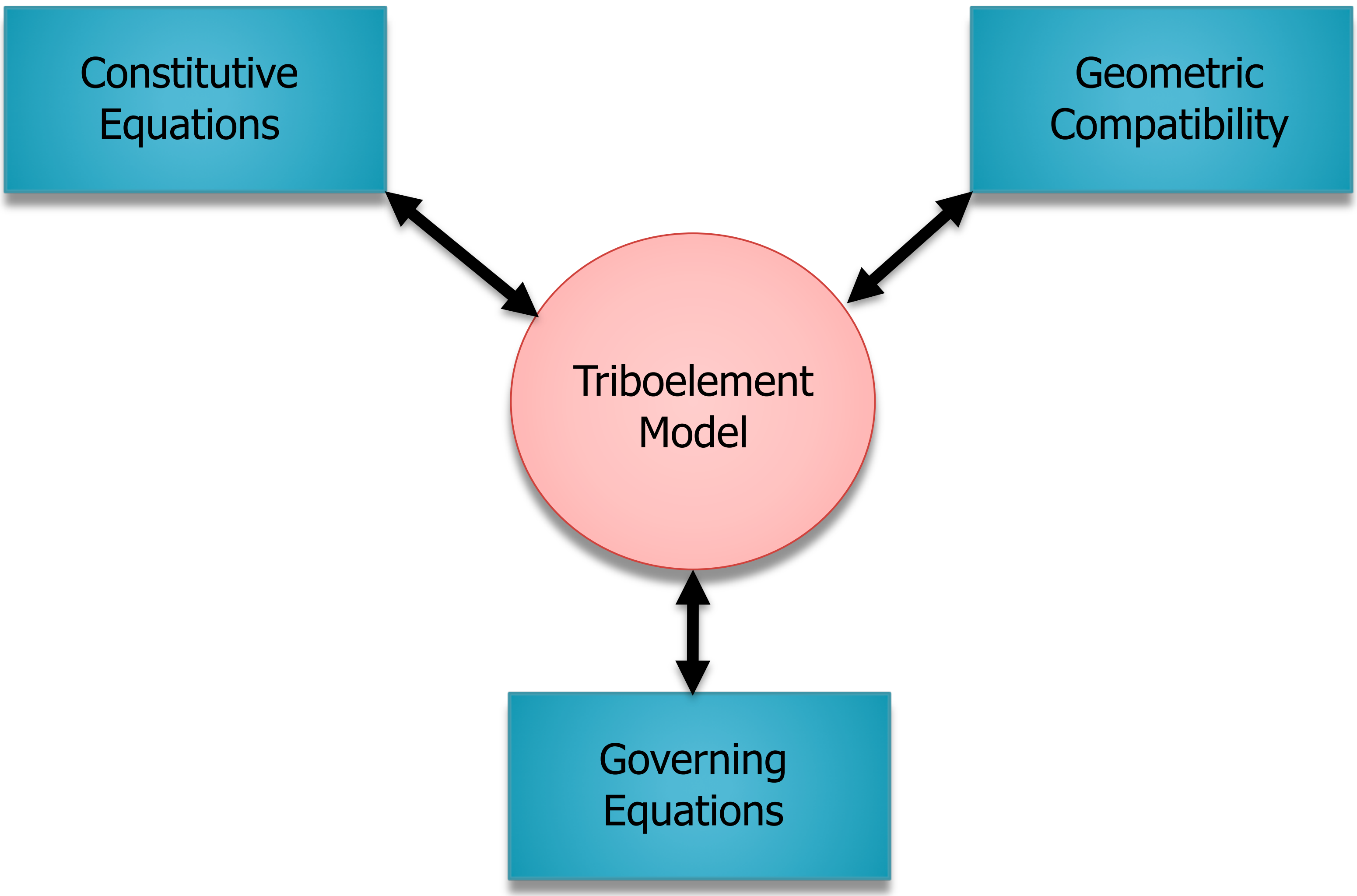
ADORE Overview Introduction

- Basic Modeling Techniques
- Stages of Development
- Evolution of ADORE

ADORE Overview
Modeling Fundamentals

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

Development Fundamentals
Model Components



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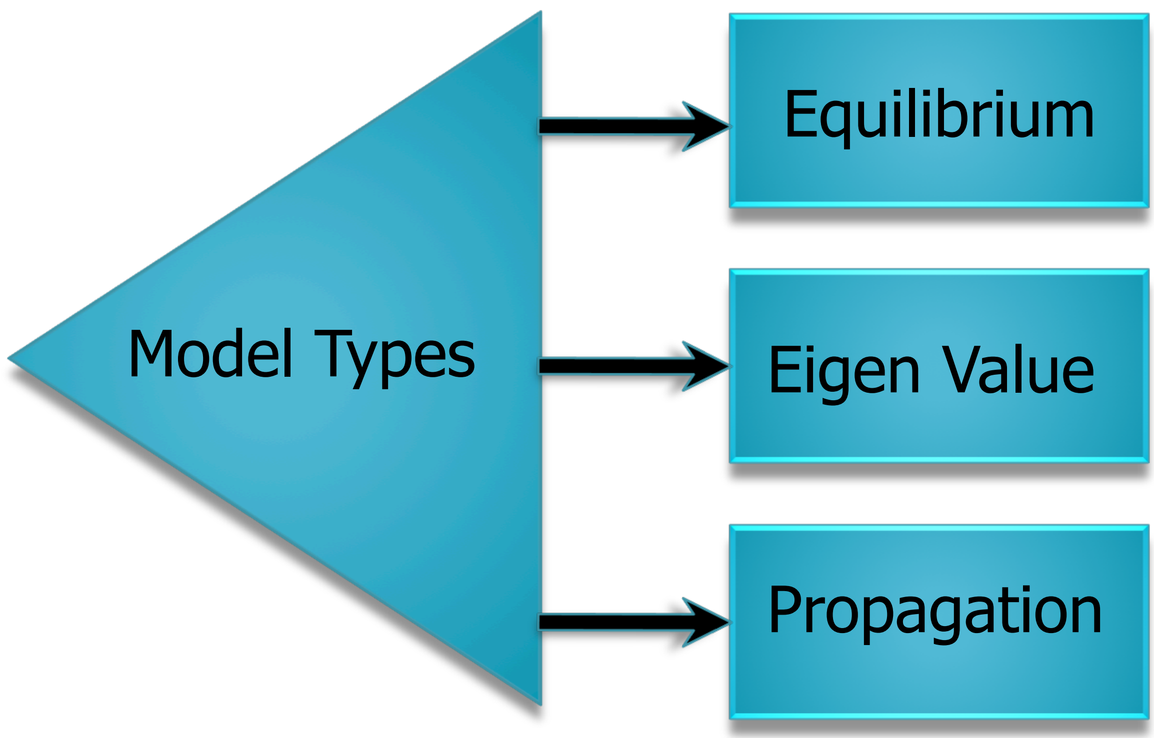
Development Fundamentals
Model Types



$$\sum F = 0$$
$$\sum G = 0$$

$$AX = \lambda BX$$

$$\sum F = m\ddot{x}$$
$$\sum G = I\dot{\omega}$$

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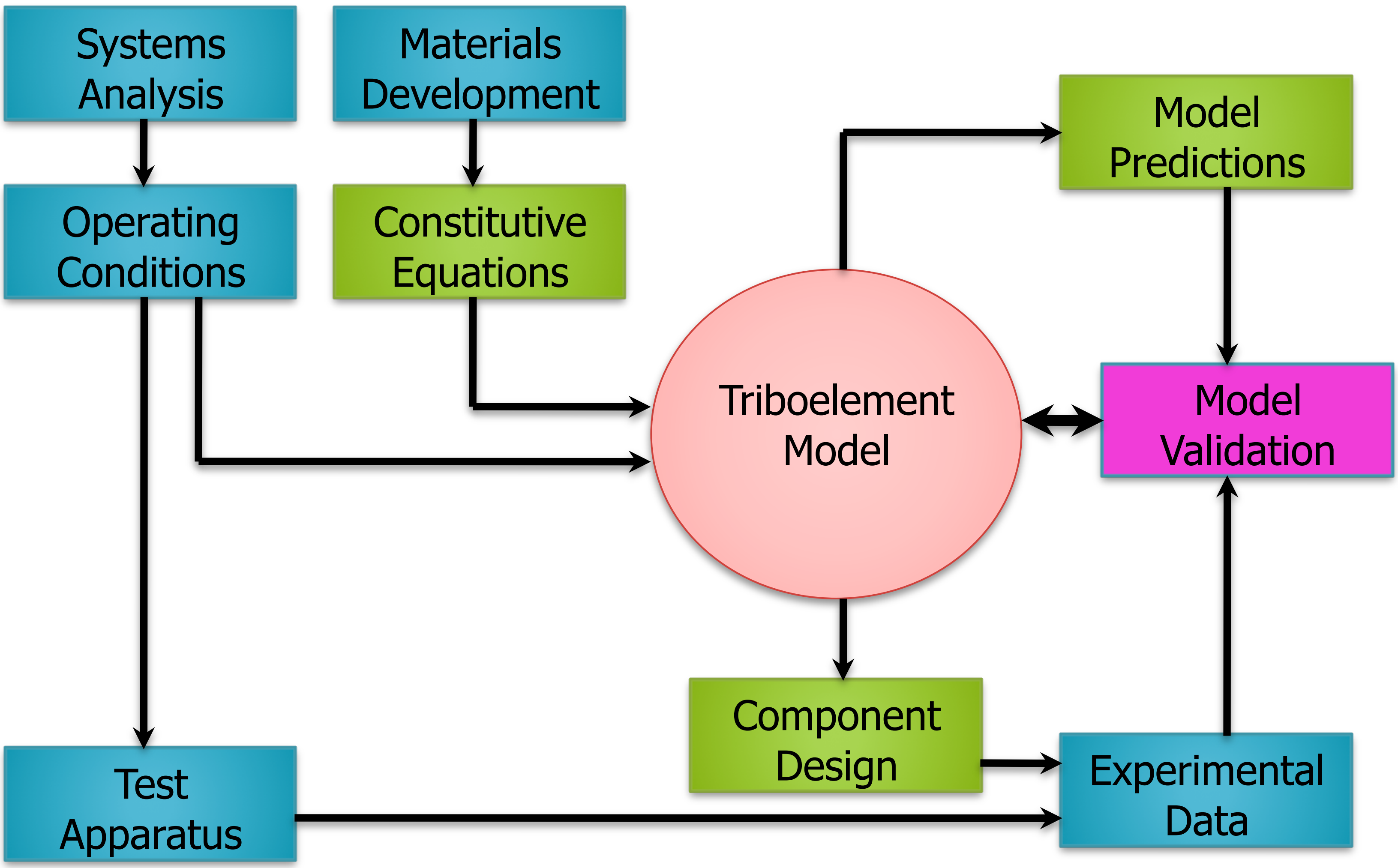
Development Fundamentals
Model Development Process



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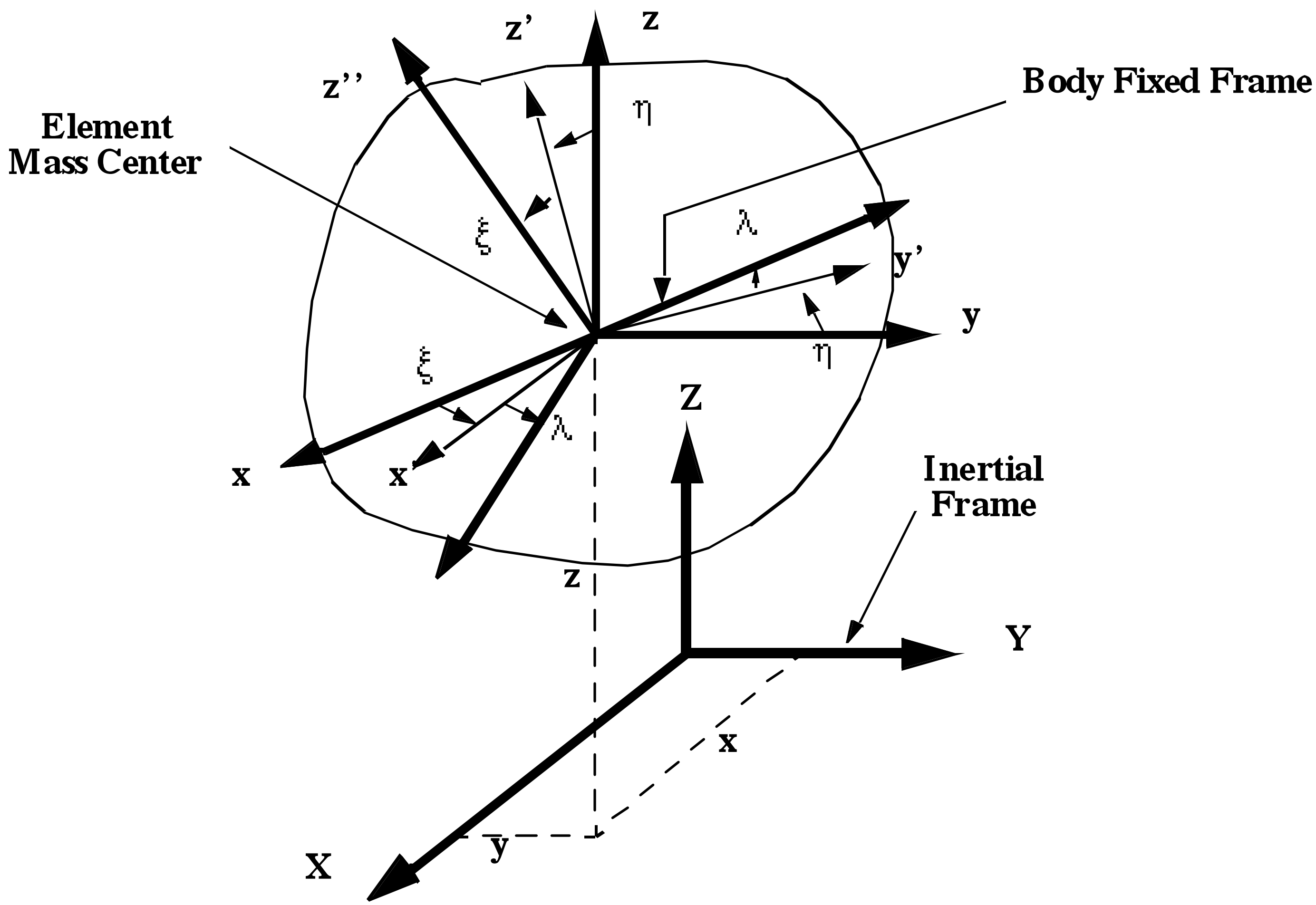
Development Fundamentals
Model Formulation

- Coordinate frames
- Element geometries
- Geometrical interactions
- Constitutive relations
- Governing equations
- Numerical solution techniques

Development Fundamentals

Base Coordinate Frames



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Development Fundamentals
Common Types of Rolling Bearing Models

- Quasi-Static models

$$\sum F = 0$$

$$\sum G = 0$$

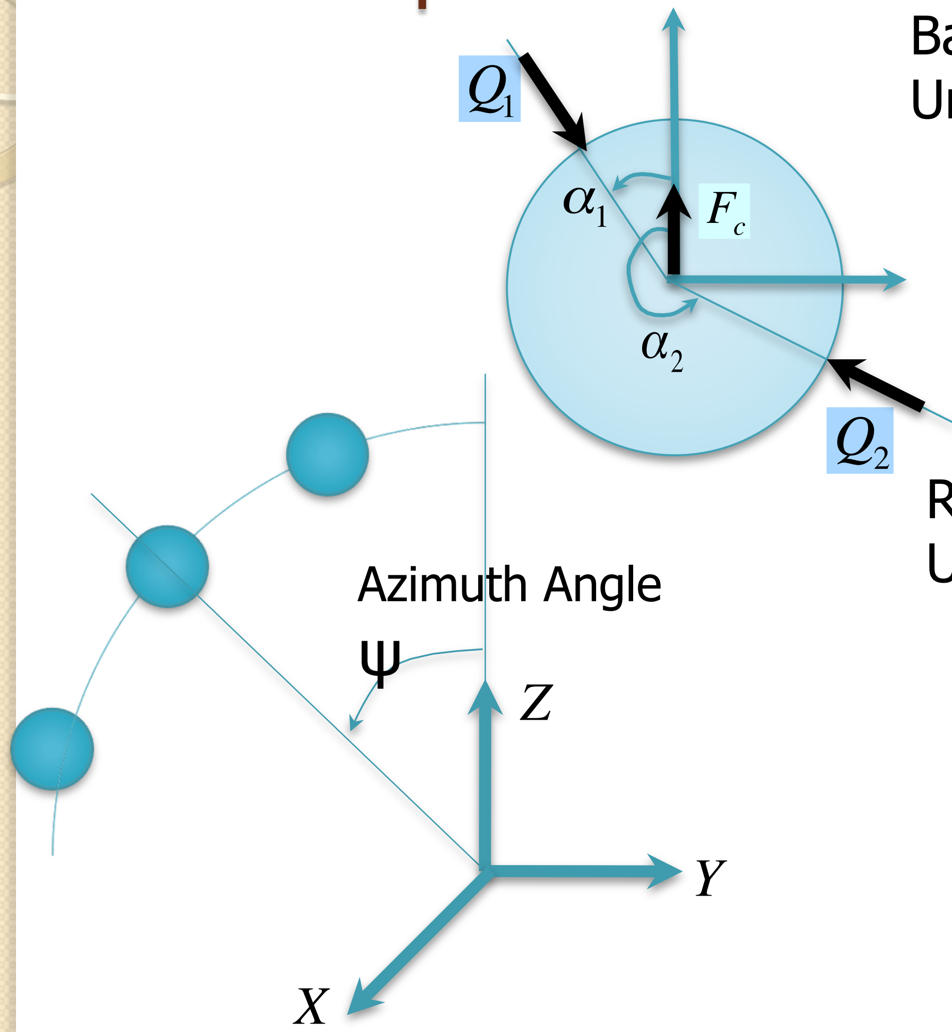
- Dynamic models

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

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

Development Fundamentals

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

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

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

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

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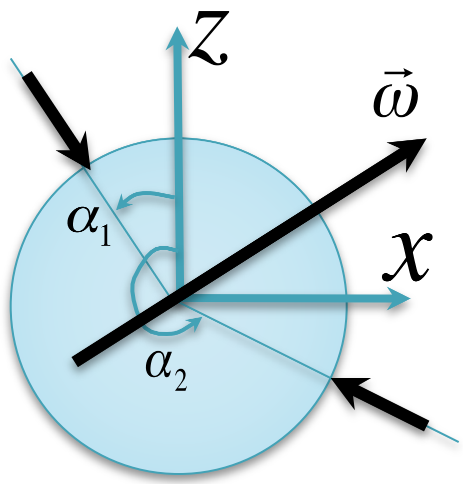
Development Fundamentals
Ball Angular Velocities

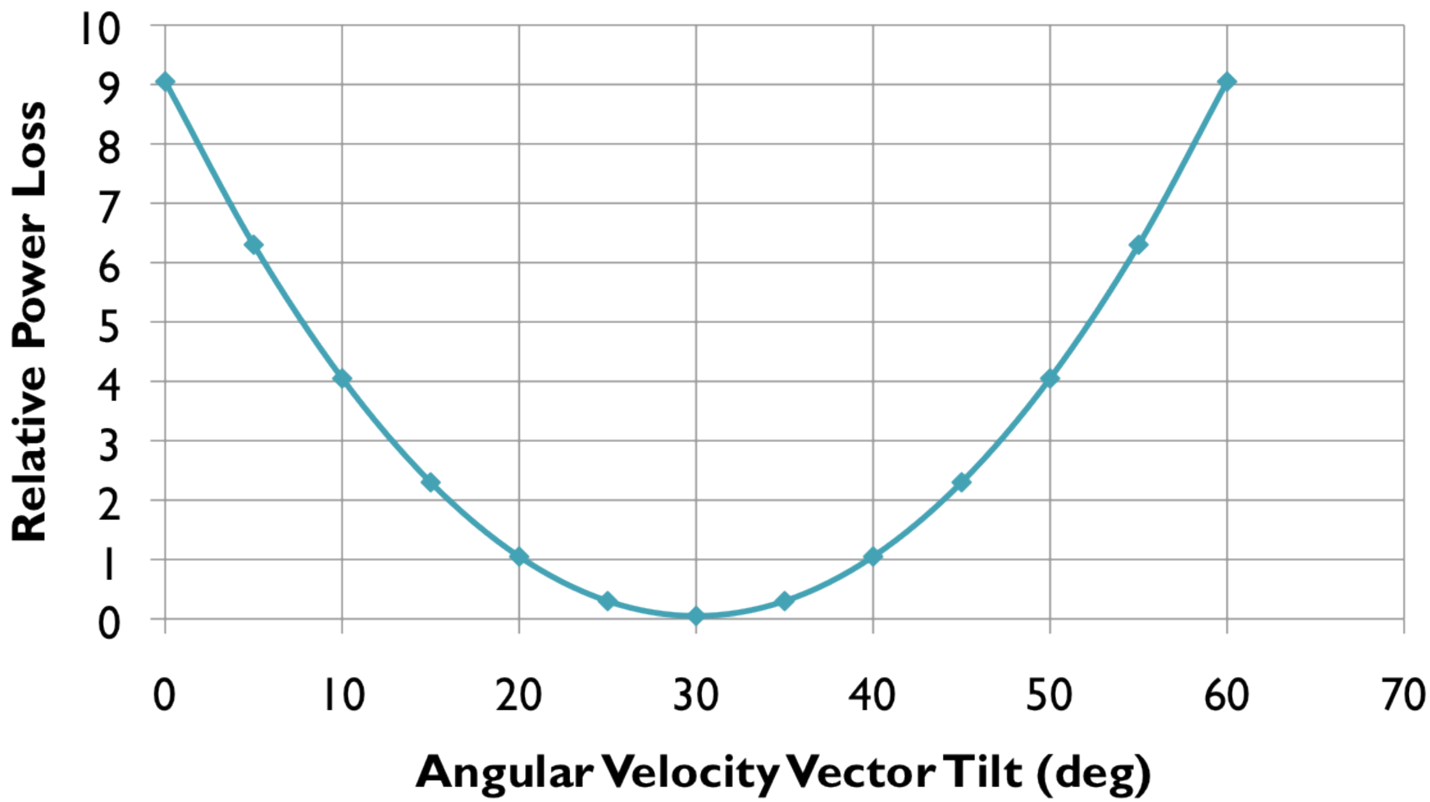


Unknowns:
- Angular Velocity Component x
- Angular Velocity Component z
- Orbital Angular Velocity

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

Development Fundamentals
Minimum Energy Constraint



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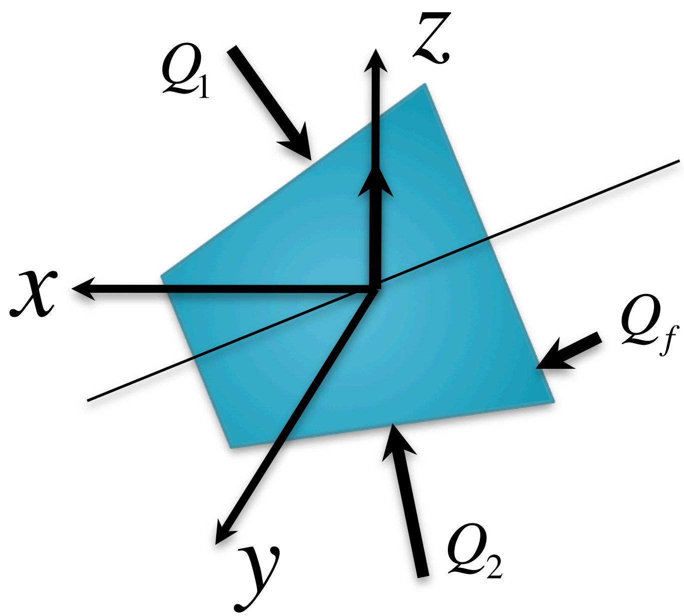
Development Fundamentals

Force and Moment Equilibrium on Roller Bearings



Unknowns:

Axial Position: x

Radial Position: z

Misalignment about y axis: θ

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

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Development Fundamentals

Dynamic Model

- Mass Center Motion

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

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

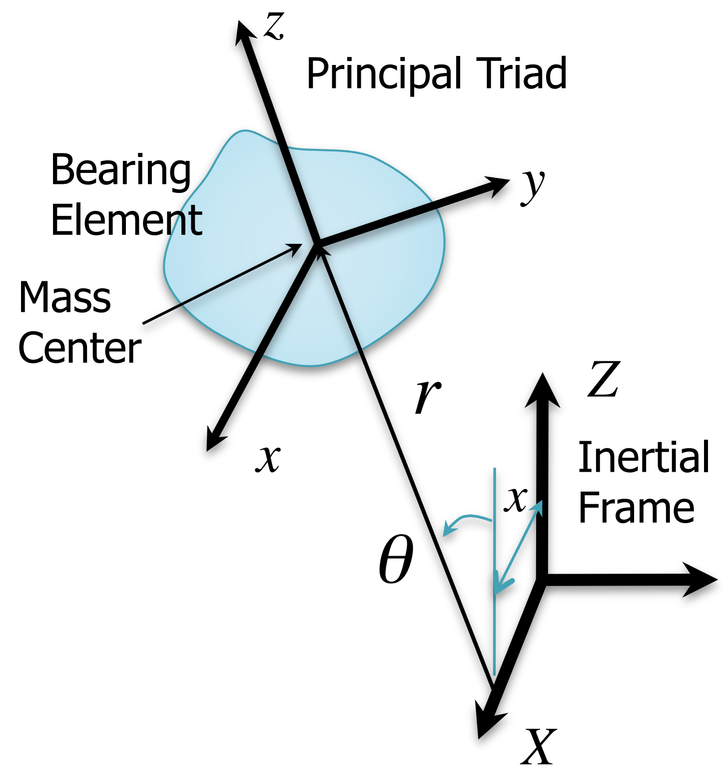
$$m\ddot{z} = F_z \qquad mr\ddot{\theta} + 2m\dot{r}\dot{\theta} = F_\theta$$

- 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

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Development Fundamentals
Model Differences

Quasi-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

Development Fundamentals

Practical Significance of the Two Types of Models

- Quasi-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 Overview

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ADORE Overview

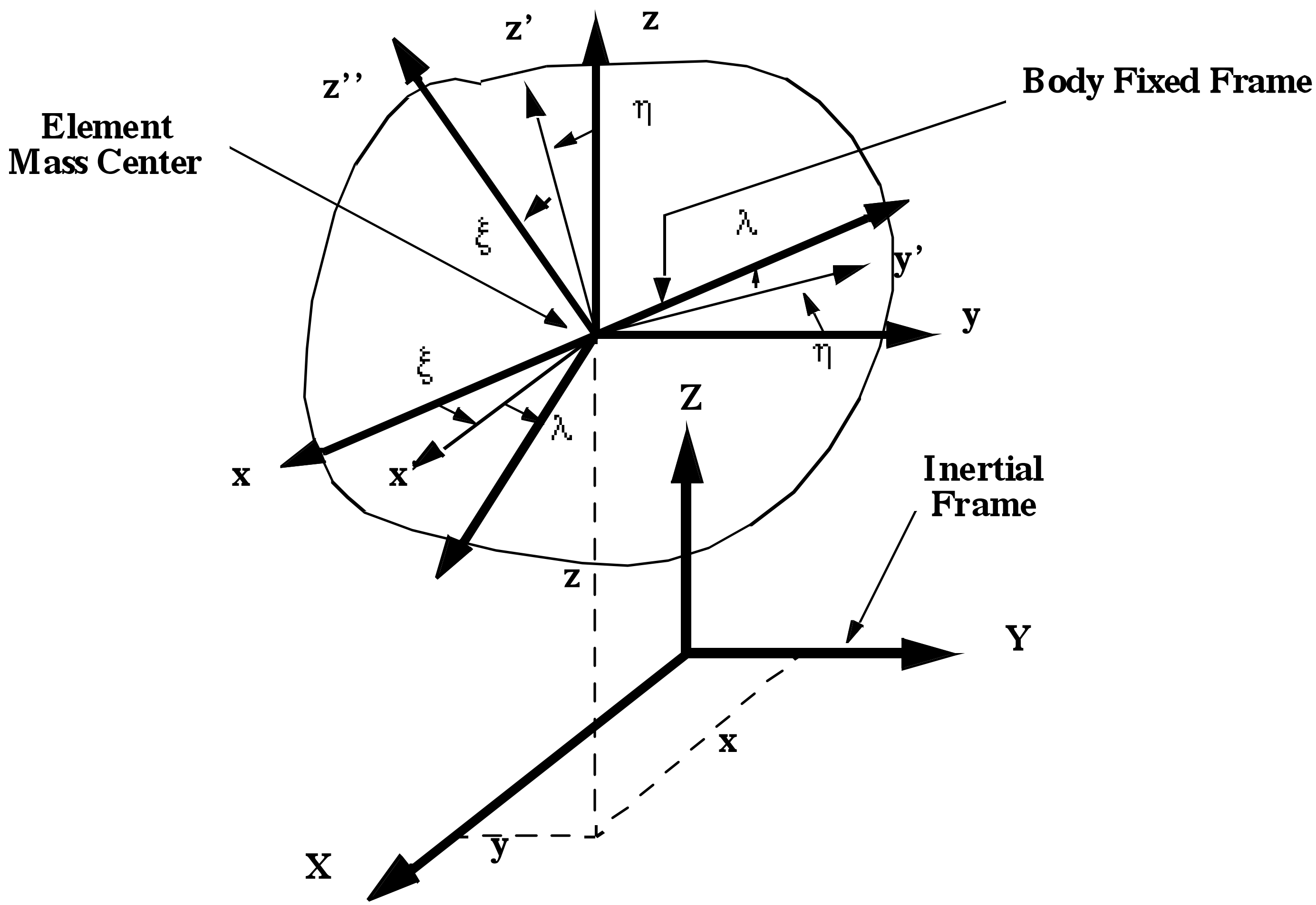
- Both types of models
  - Quasi-static
  - Real-time dynamic
- Primary purpose of quasi-static model
  - Estimation of initial conditions for dynamic simulation
- Eigen value modeling
  - Control on time step
  - Real-time bearing element acceleration
  - Post processing – Fast Fourier transform

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



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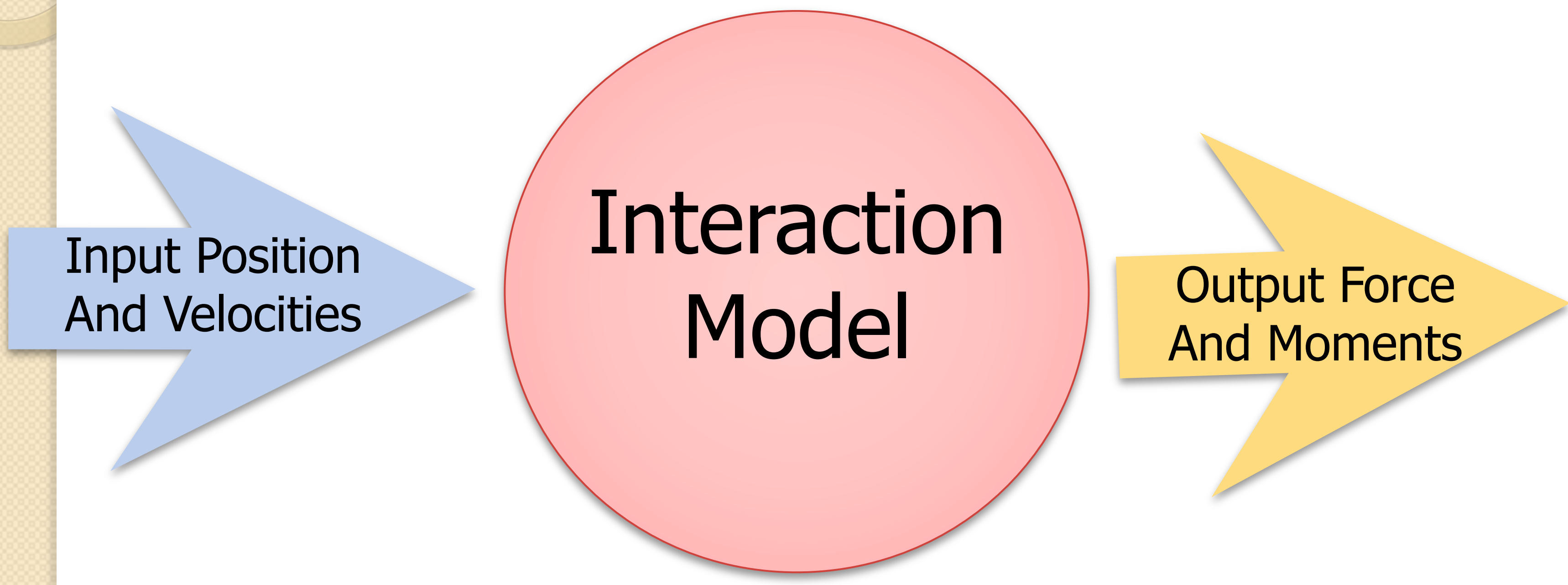
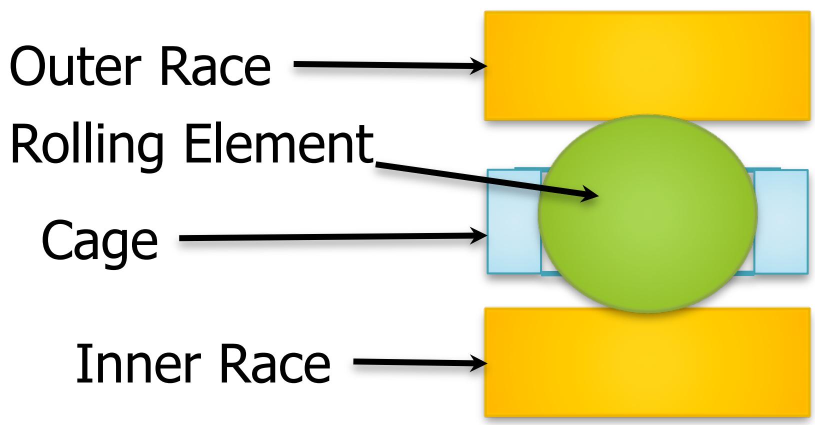
Interaction Model

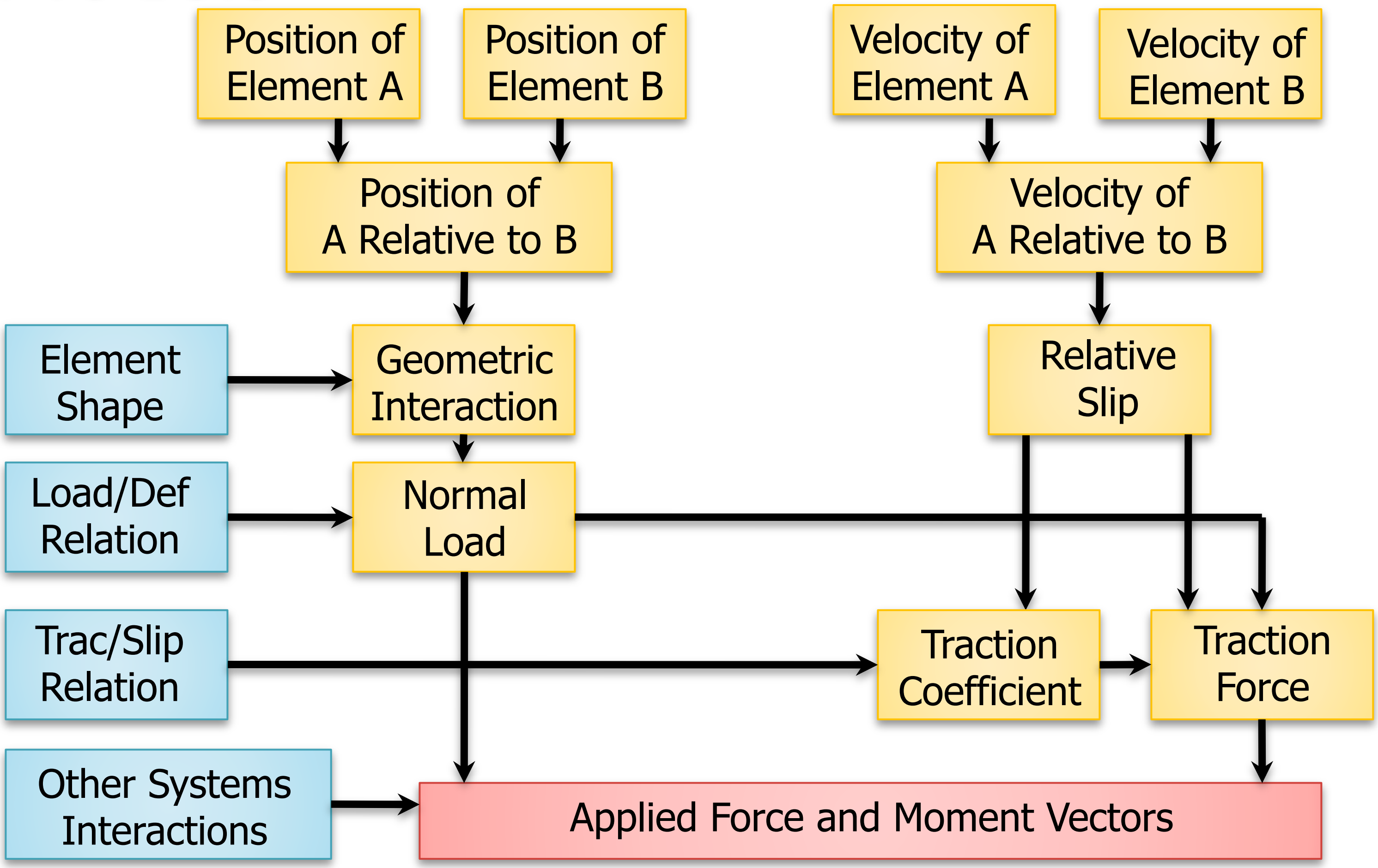


Elements of a Rolling Bearing

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



Generic Architecture of Interaction Models



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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 computions
  - Multi-dimensional arrays
  - Floating point processing speeds
  - Complex numbers

Rolling Bearing Models
Historic Perspective

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

Rolling Bearing Models

Historic Perspective

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

Rolling Bearing Models

Historic Perspective

Quasi-Static Models	Time	Dynamic Models
	1994	AGORE - Gupta
		BASDREL, BABERDYN - Meeks
	1999	BEAST – 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".

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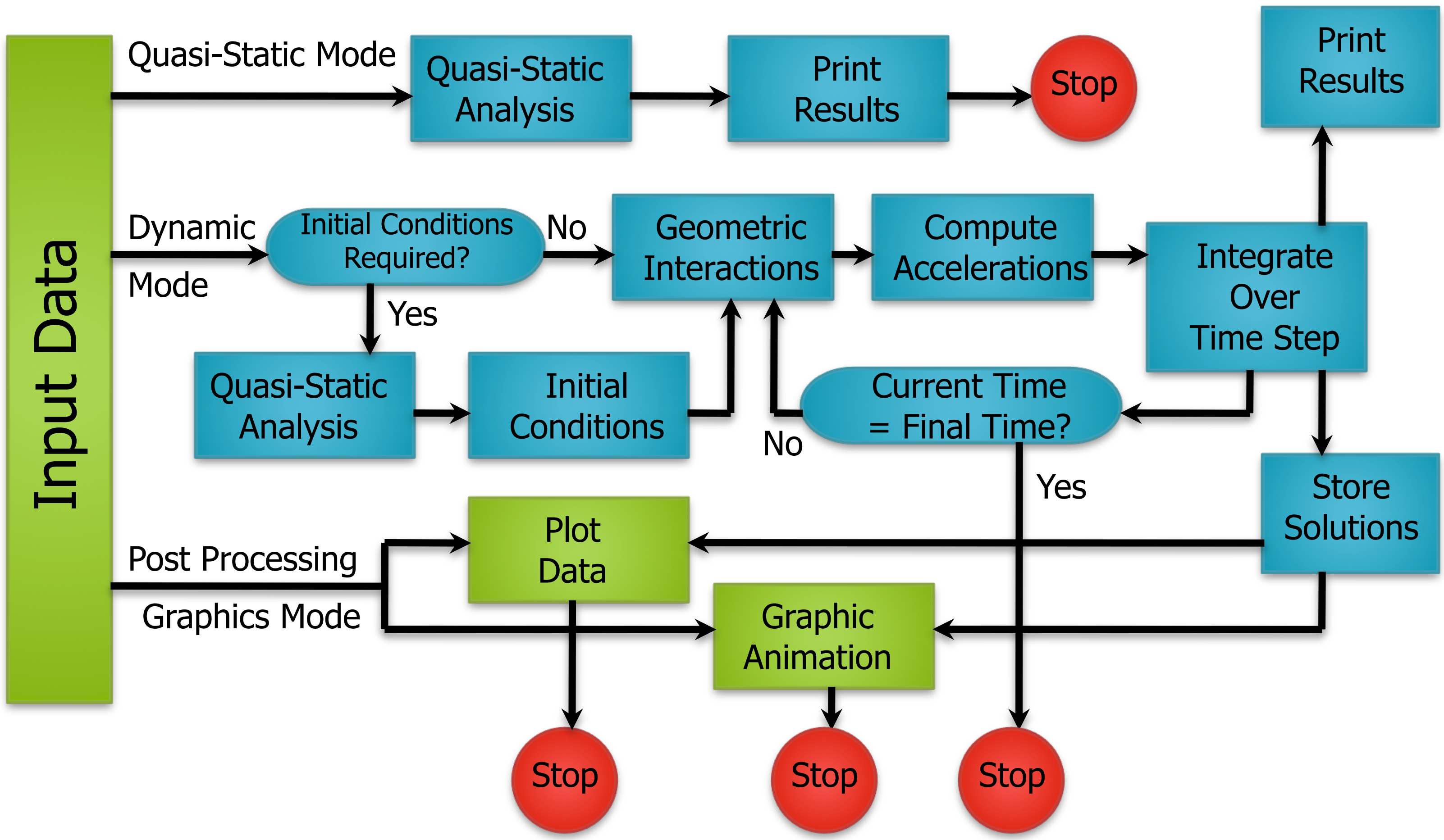
ADORE Overview
Development Time Line

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
Simplified Flow Chart



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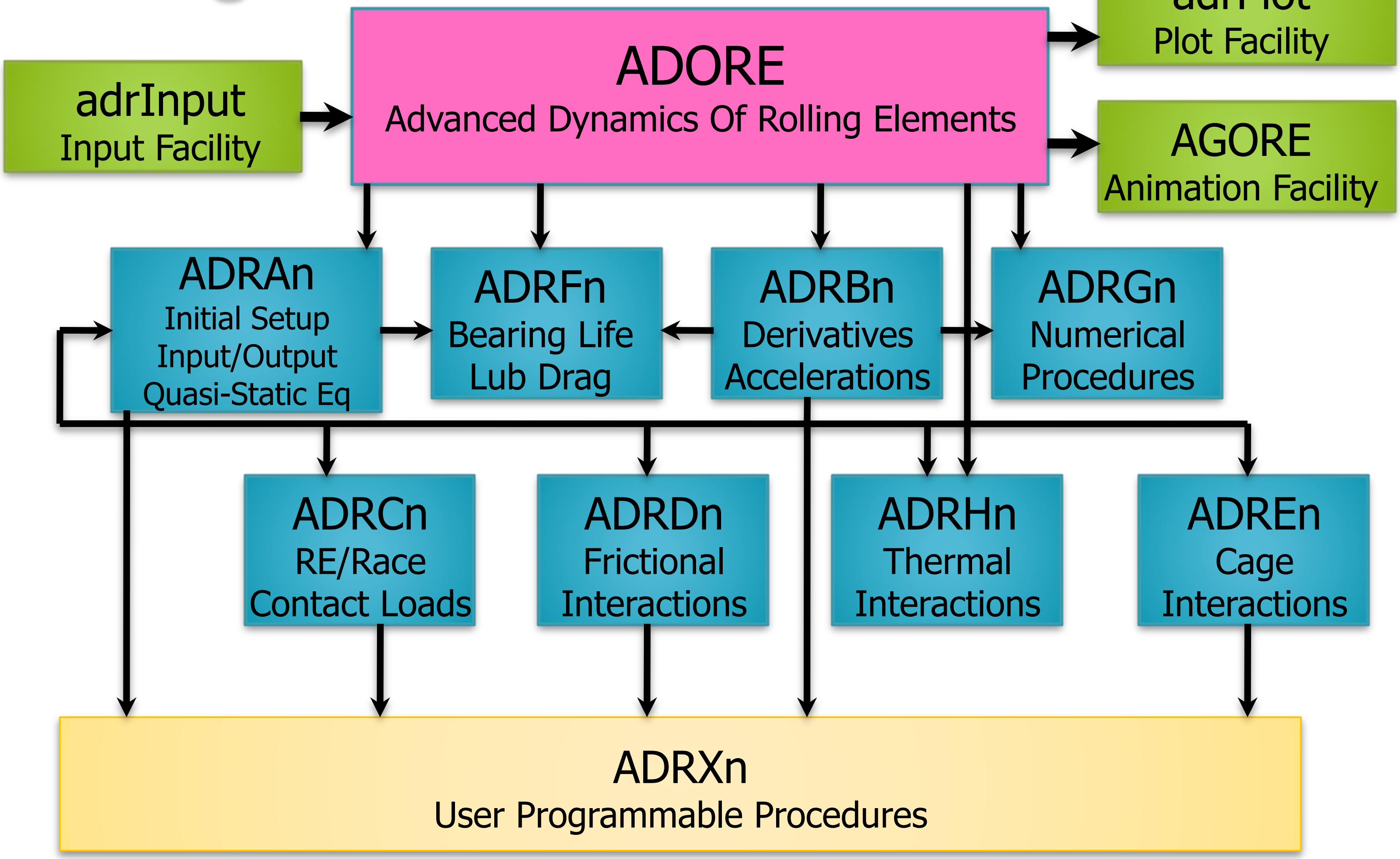
ADORE Overview
Program Modules



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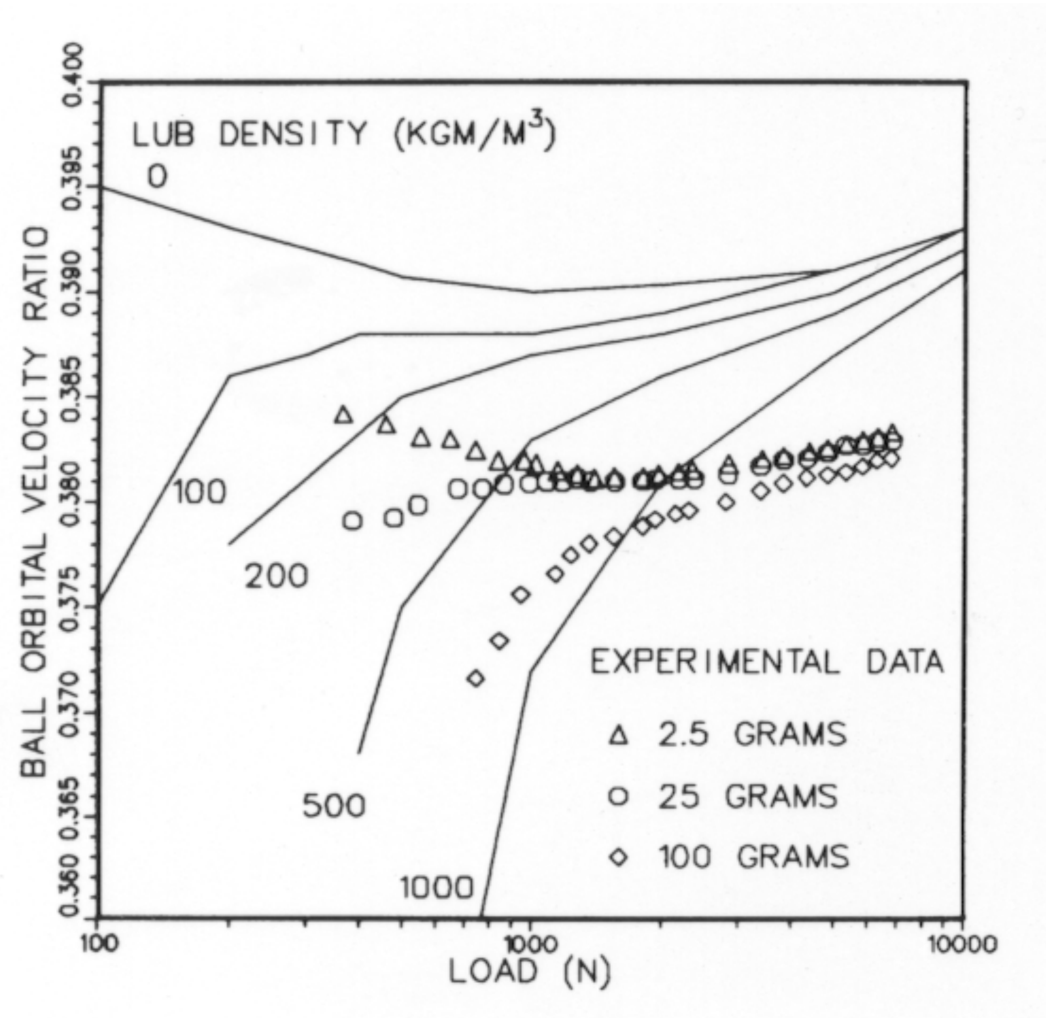
ADORE Overview
Experimental Validation

- Bearing failures in the field
- Ball skid
- Cage motion

ADORE Experimental Validation
Ball Skid



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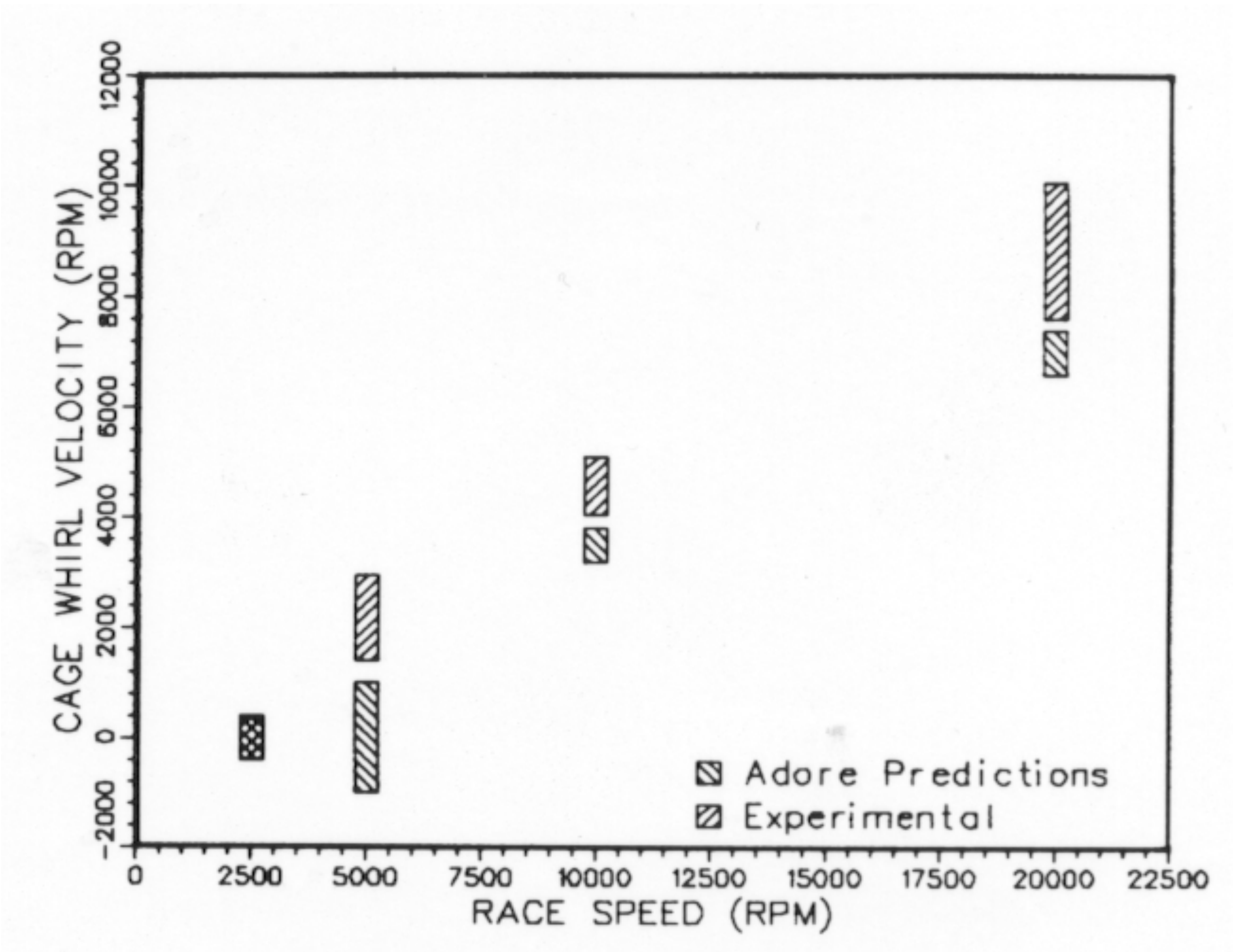
ADORE Experimental Validation Cage Whirl Motion



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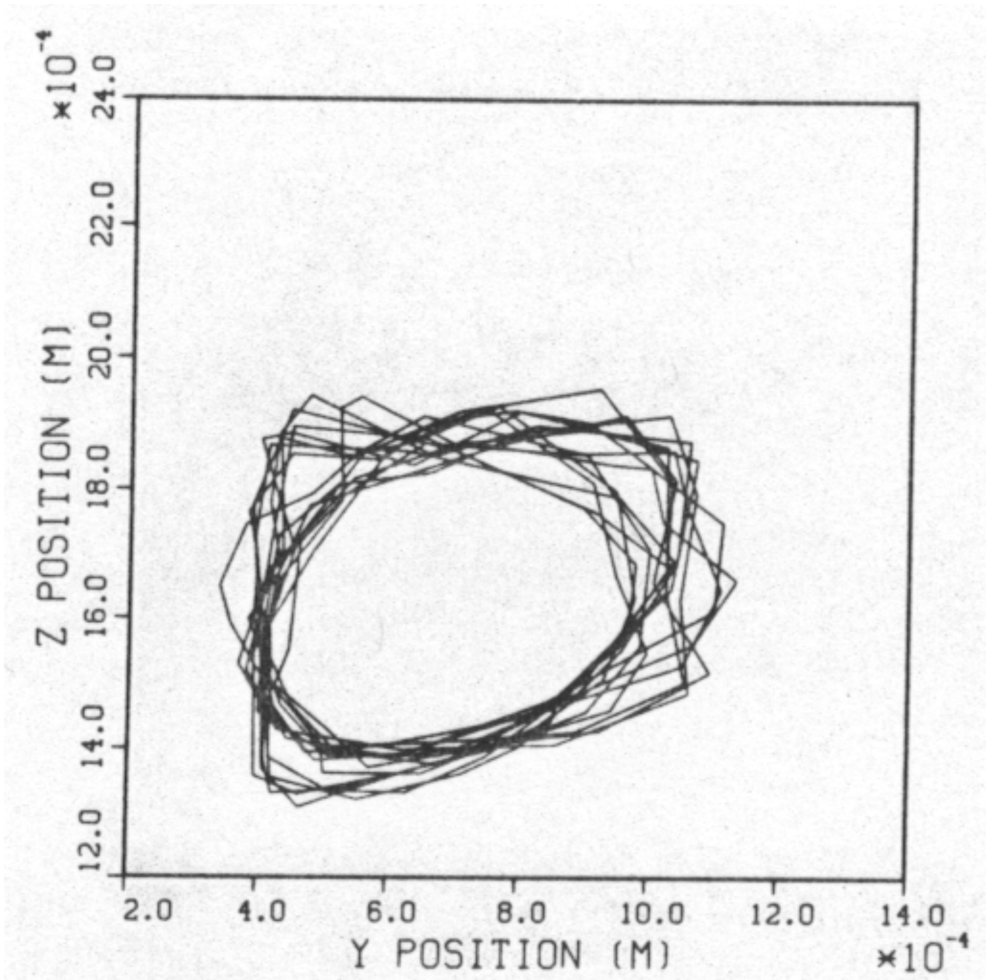
ADORE Experimental Validation

Cage Unbalance – Circular Whirl Orbits



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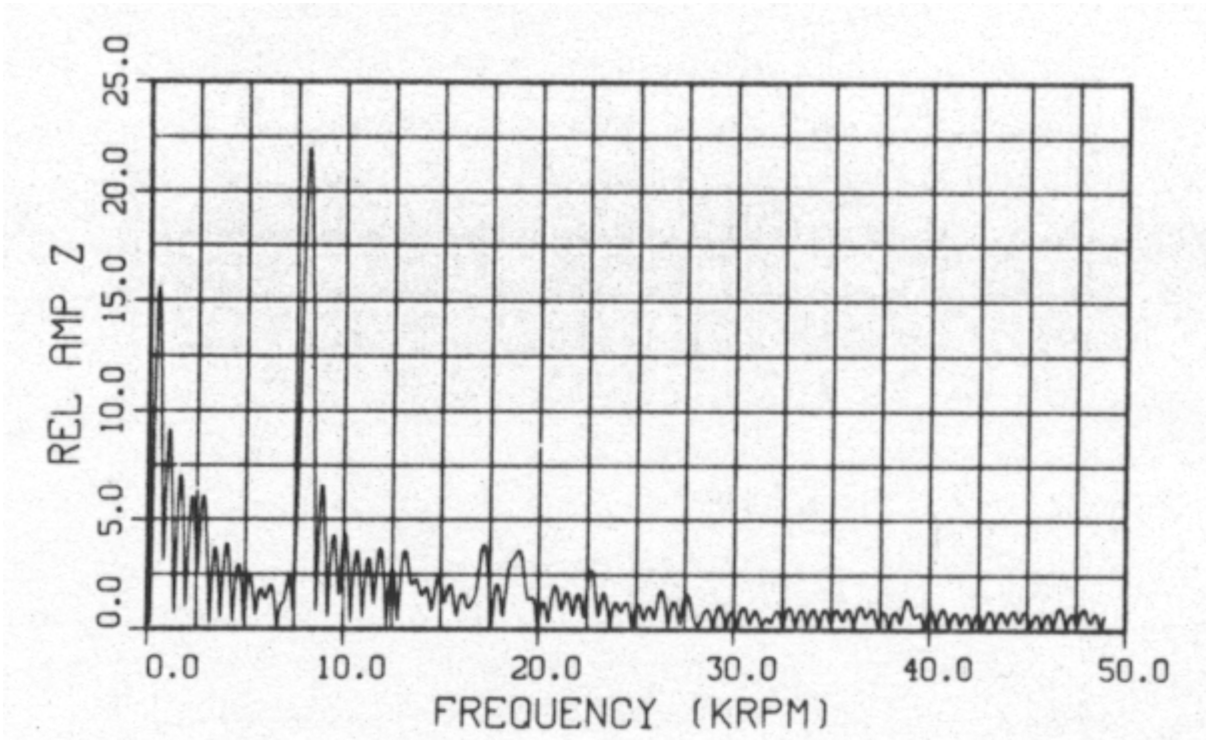
ADORE Experimental Validation

Cage Unbalance – Whirl Vel = Cage Ang Vel



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ADORE Experimental Validation

Cage Unbalance – Damage vs Unbalance

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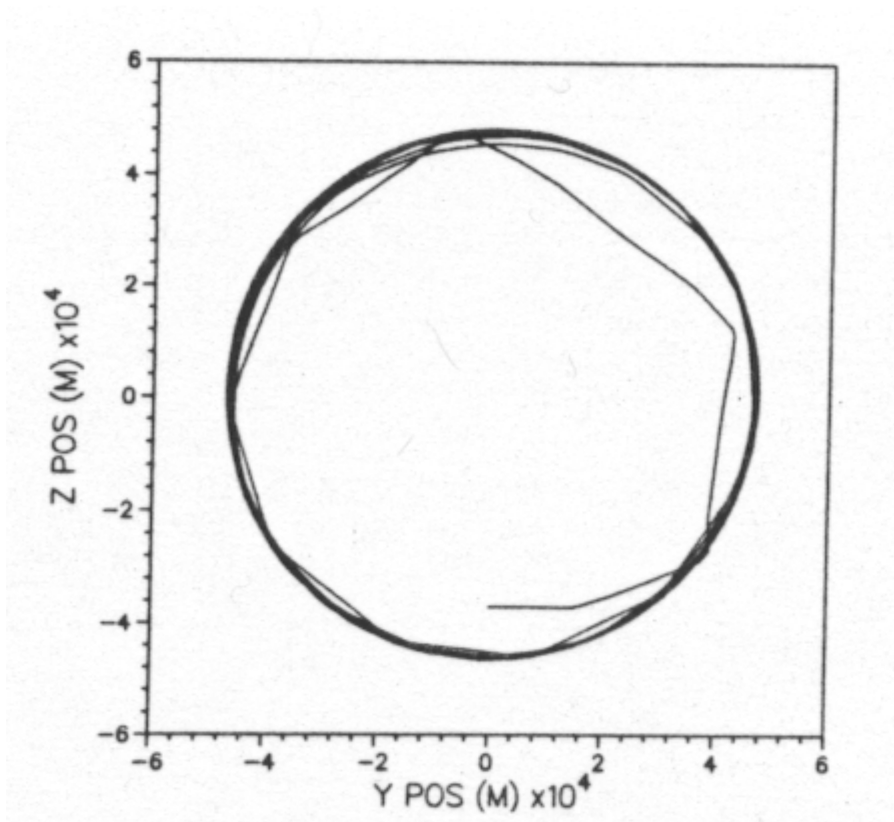
ADORE Experimental Validation

Cage Unbalance – Circular Whirl Orbits



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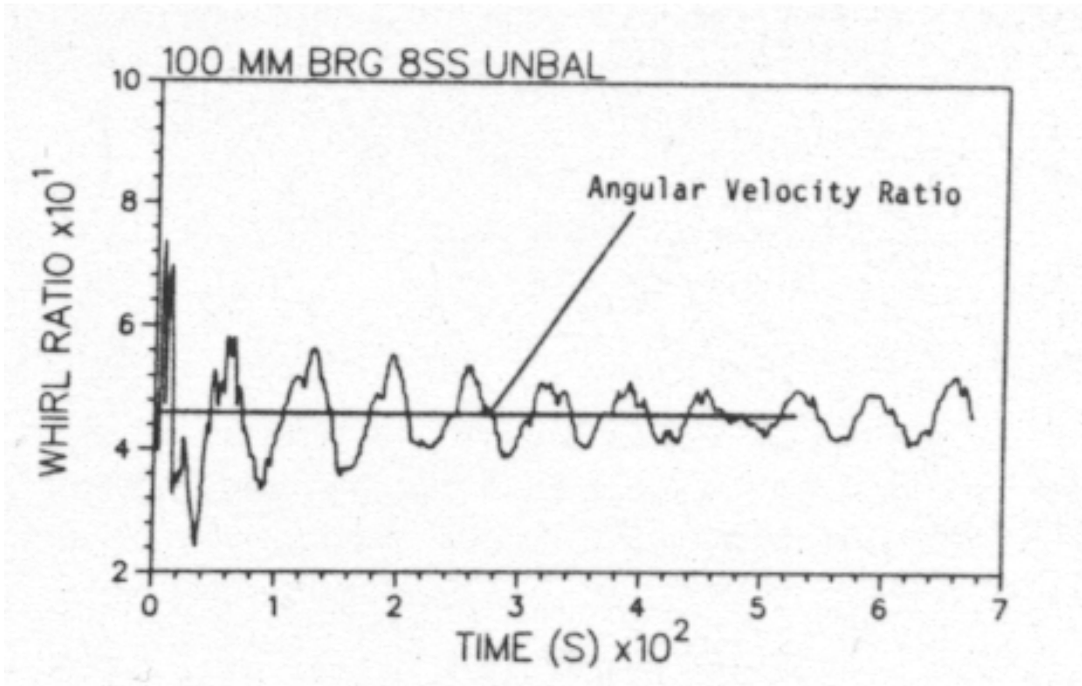
ADORE Experimental Validation

Cage Unbalance – Whirl Vel = Cage Ang Vel



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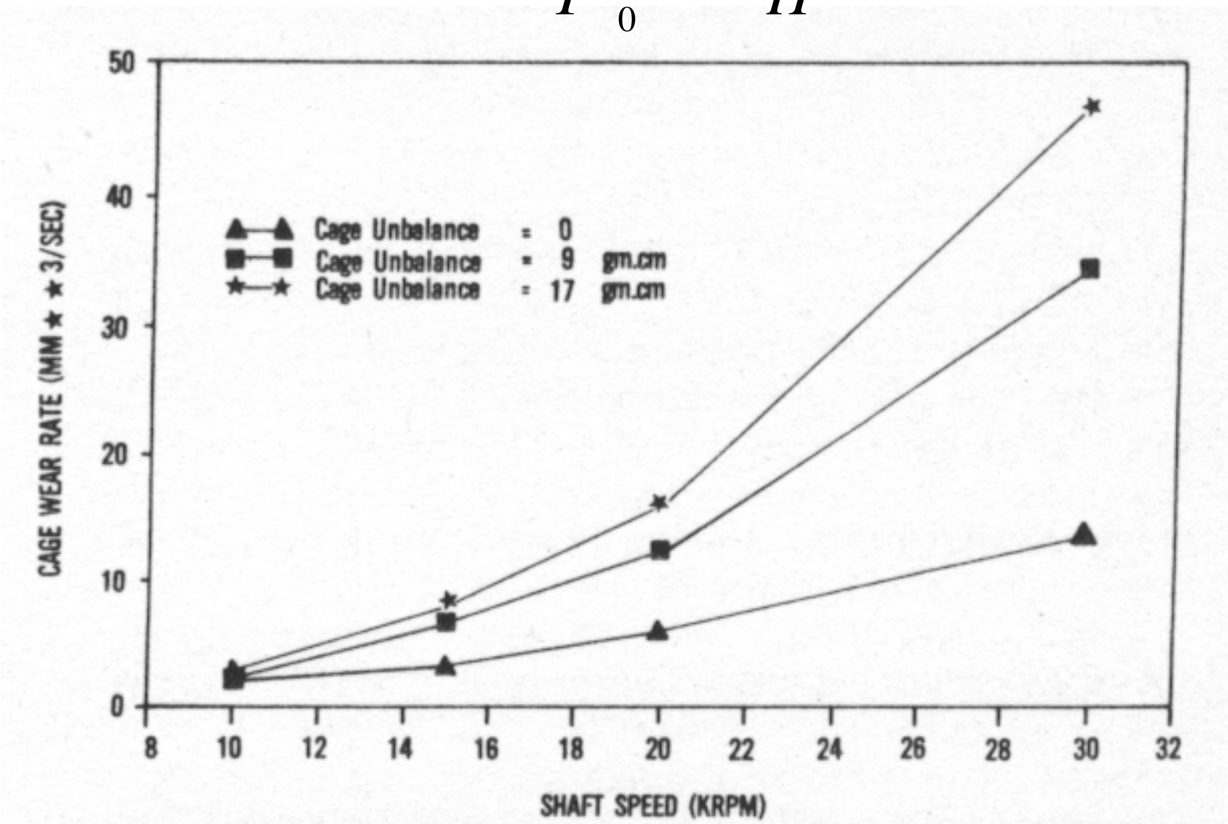
ADORE Experimental Validation

Cage Unbalance – Damage vs Unbalance

$$W(T) = \frac{1}{T}\int_0^T \frac{KQ(t)V(t)}{H}dt$$



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ADORE Overview

Significant Parameters in Dynamic Modeling

- Rolling element to race traction
- Cage friction coefficients
- Cage pocket clearances
- Cage/Race guide clearance

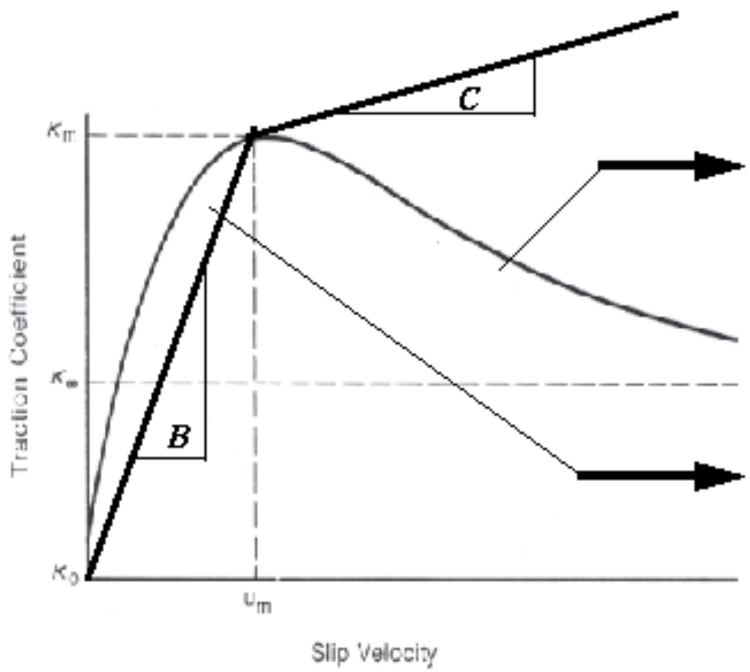
ADORE Overview

Traction Models

- Hypothetical models
- Elastohydrodynamic models
  - Newtonian models
  - Visco-elastic models

Traction Models in ADORE

Hypothetical Model



$$\kappa = (A + Bu)e^{Cu} + D$$

When $\kappa = \kappa_o = 0$, at $u = 0$, $D = -A$, Thus,

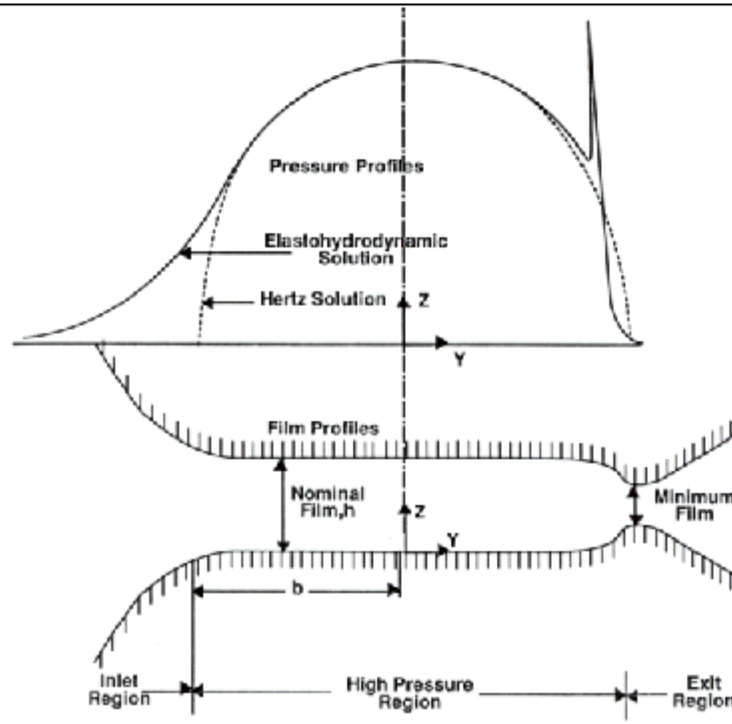
$$\kappa = (A + Bu)e^{Cu} - A$$

$$\kappa = Bu,\ u < u_m \text{ and } \kappa = \kappa_o \text{ at } u = 0$$

$$\kappa = \kappa_m + C(u - u_m),\ u > u_m$$

Traction Models in ADORE

Elastohydrodynamic Models



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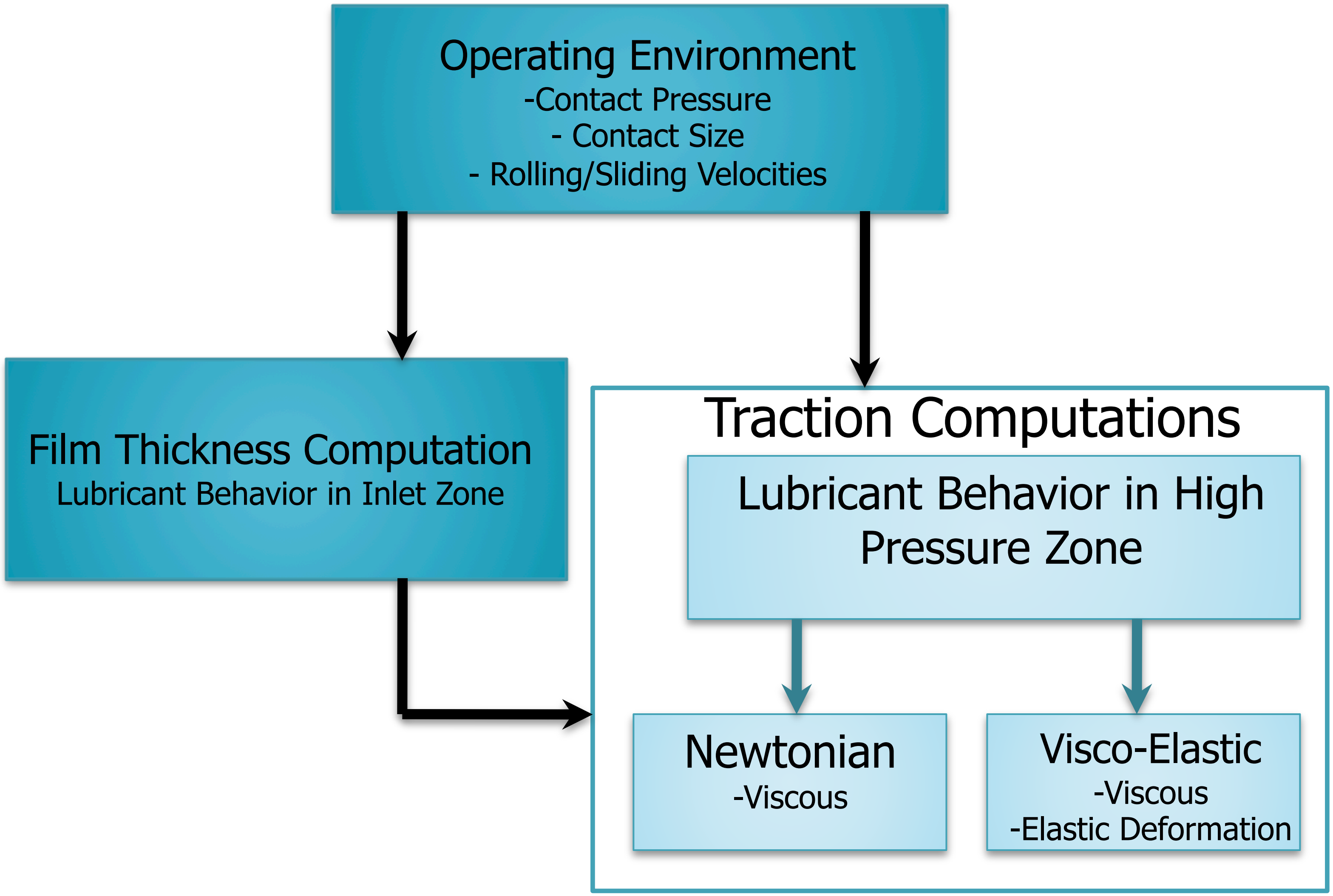
Traction Models in ADORE

Elastohydrodynamic Models – Model Schematic



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Traction Models in ADORE

Elastohydrodynamic Models – Newtonian Model

- Energy Equation $$K\frac{\partial^2 T}{\partial z^2} = -\tau\dot{s}$$
- Geometric Compatibility $$\frac{\partial u}{\partial z} = \dot{s}(\tau, p, T)$$
- Constitutive Equation $$\dot{s}(\tau, p, T) = \frac{\tau}{\mu(p,T)}$$
  - Type I $$\mu = \mu_o \exp[\alpha p + \beta(T_o - T)]$$
  - Type II $$\mu = \mu_o \exp[\alpha p + \beta(\frac{1}{T} - \frac{1}{T_o})]$$

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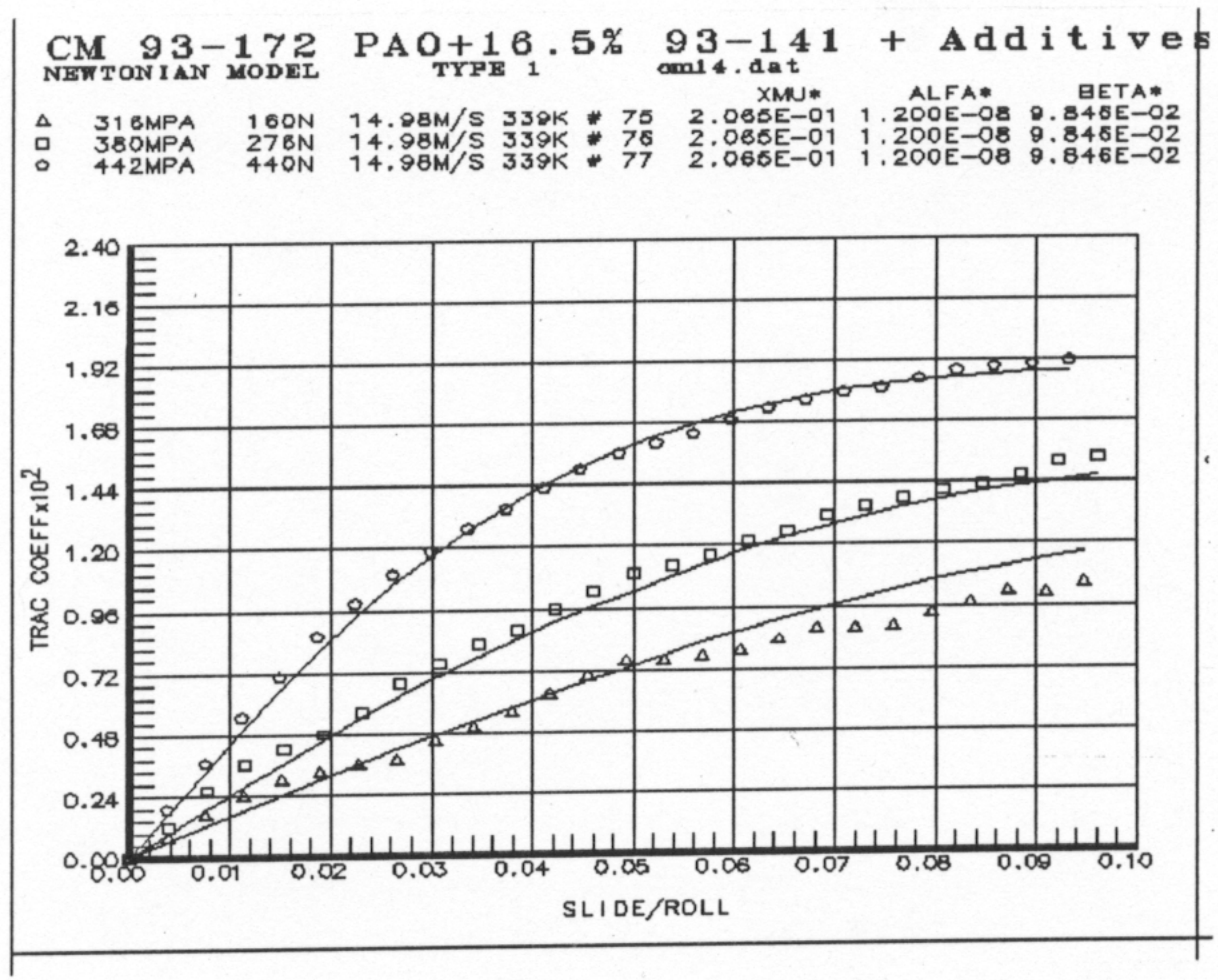
Traction Models in ADORE

Newtonian Model Validation



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Traction Models in ADORE

Visco-Elastic Models

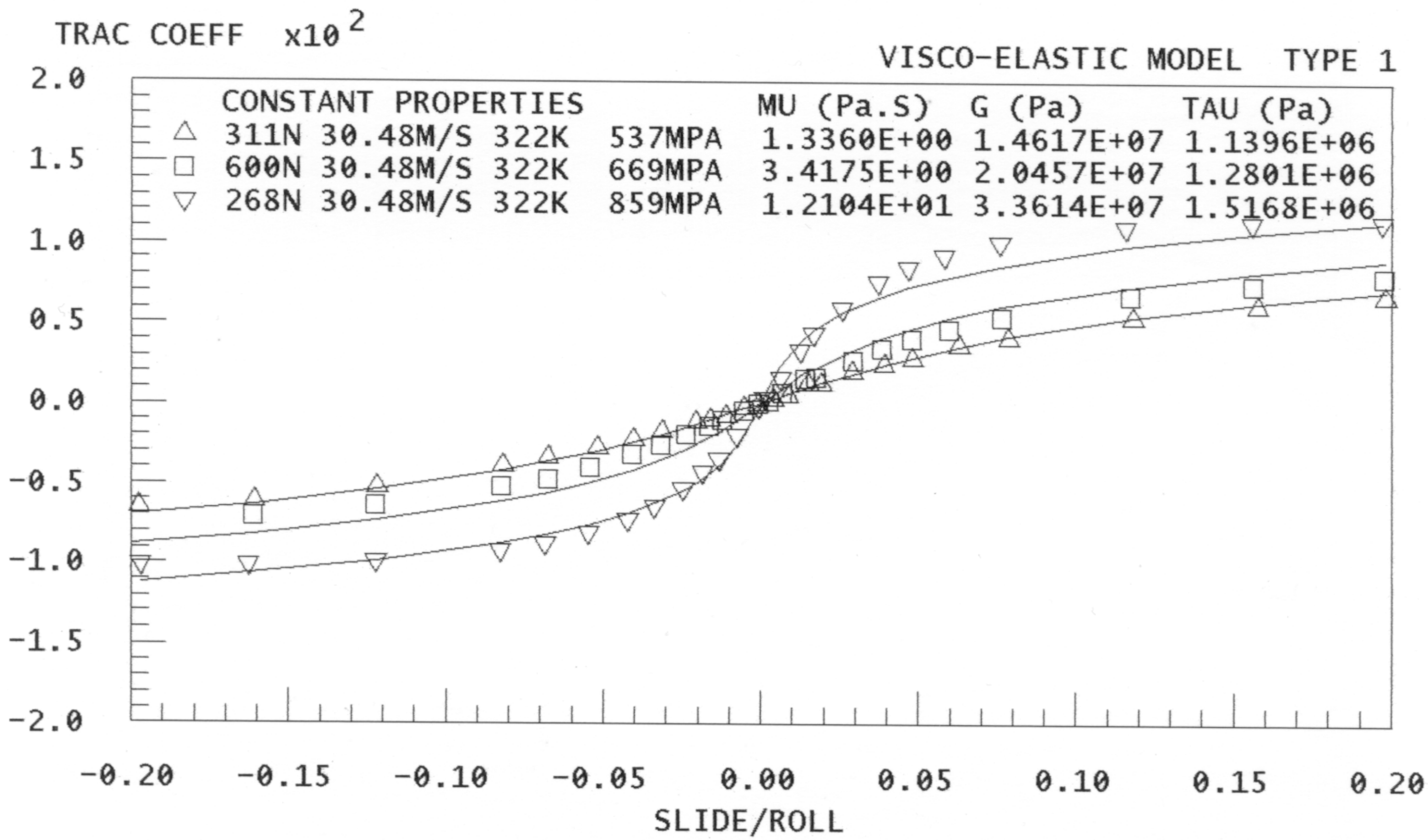
- Shear stress - strain rate equation

$$\dot{s} = \frac{1}{G}\frac{\partial \tau}{\partial t} + \frac{\tau_o}{\mu} f(\frac{\tau}{\tau_o})$$

  - Type I $\quad f(\frac{\tau}{\tau_o}) = a\sinh(\frac{\tau}{\tau_o})$
  - Type II $\quad f(\frac{\tau}{\tau_o}) = a\tanh(\frac{\tau}{\tau_o})$
- Viscosity relations
  - Type I $\quad \mu = \mu_o \exp[\alpha p + \beta(T_o - T)]$
  - Type II $\quad \mu = \mu_o \exp[\alpha p + \beta(\frac{1}{T} - \frac{1}{T_o})]$

Traction Models in ADORE

Visco-Elastic Model Validation



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ADORE Overview

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ADORE Overview
Examples

- Rolling element skid
- Geometrical imperfections
- Cage stability

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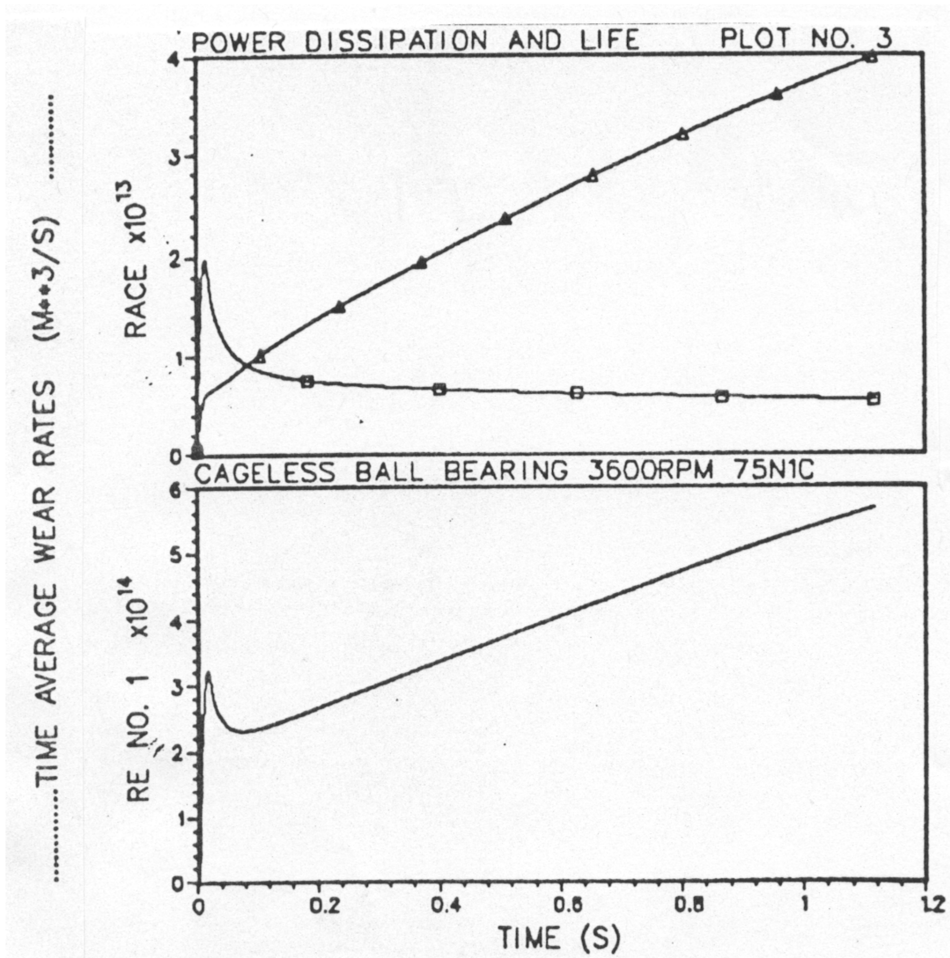
ADORE Examples

Rolling Element Skid Instability



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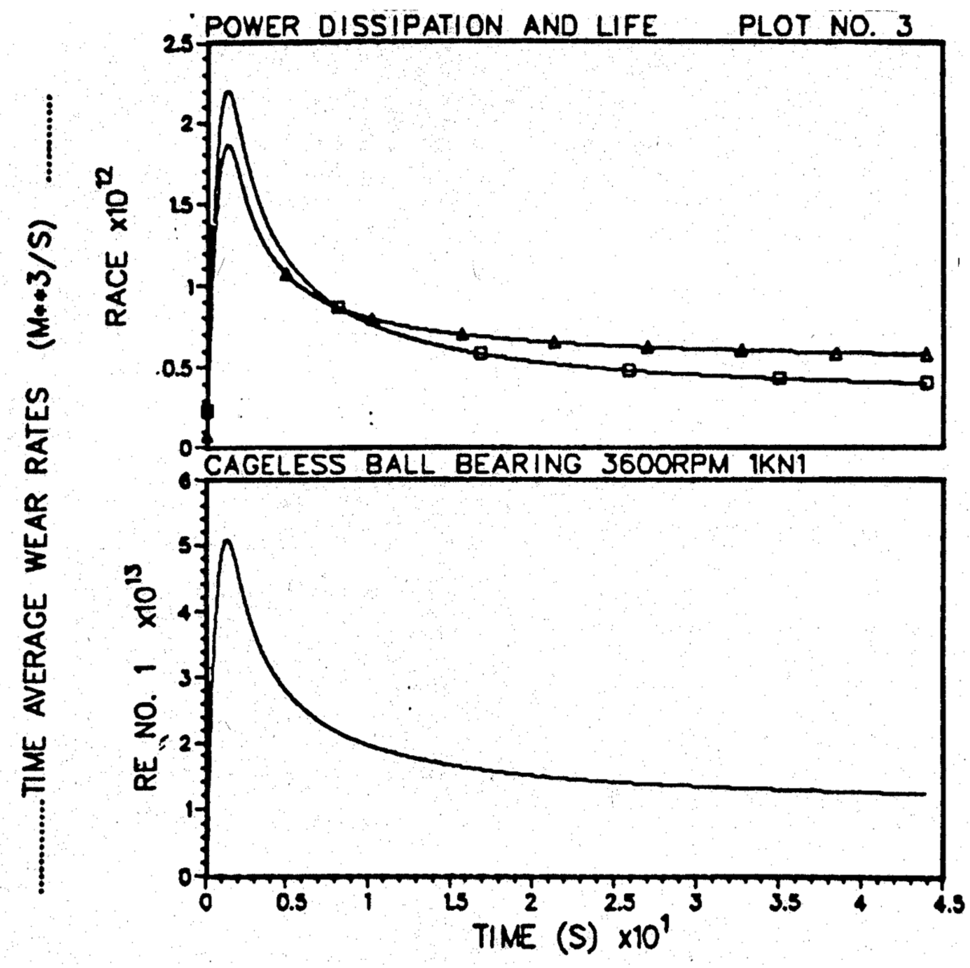
ADORE Examples

Rolling Element Skid –Stable Behavior



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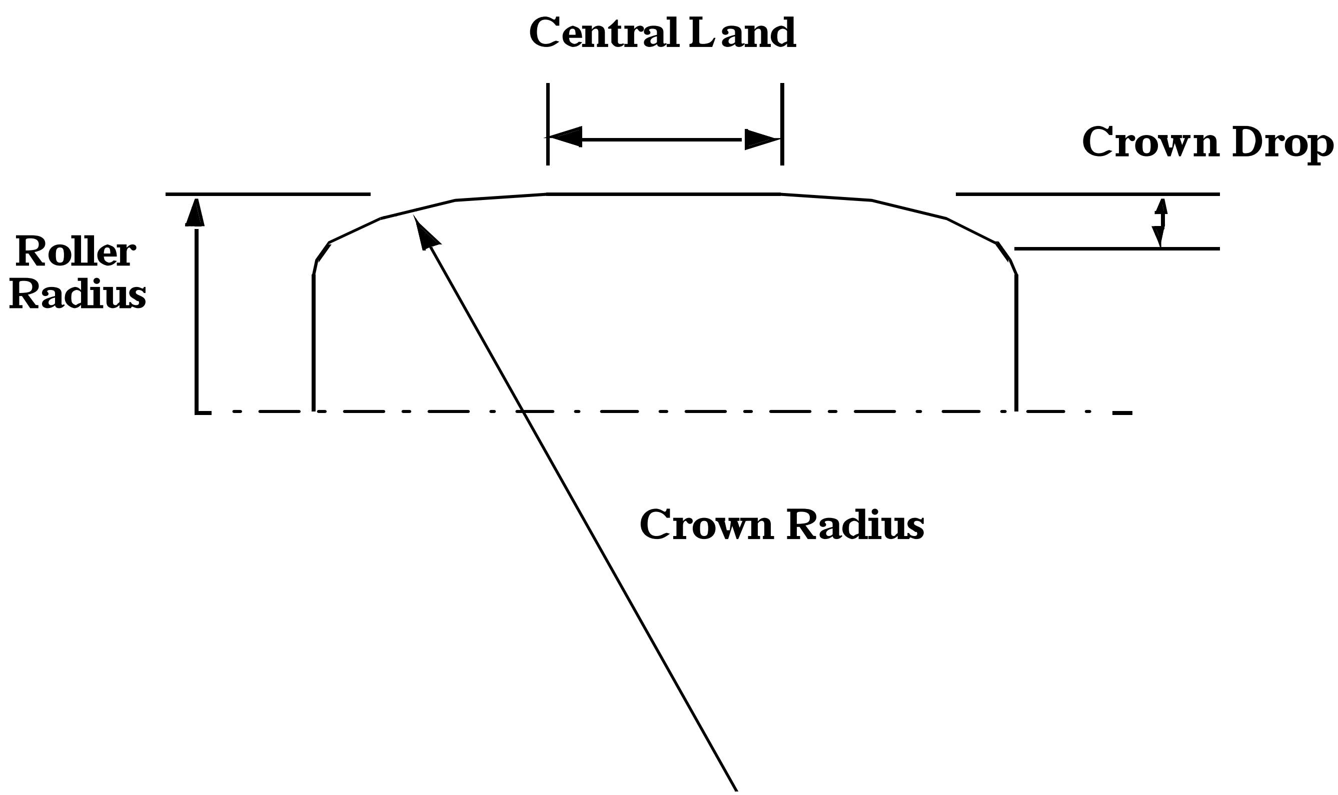
ADORE Examples

Roller Land Schematic



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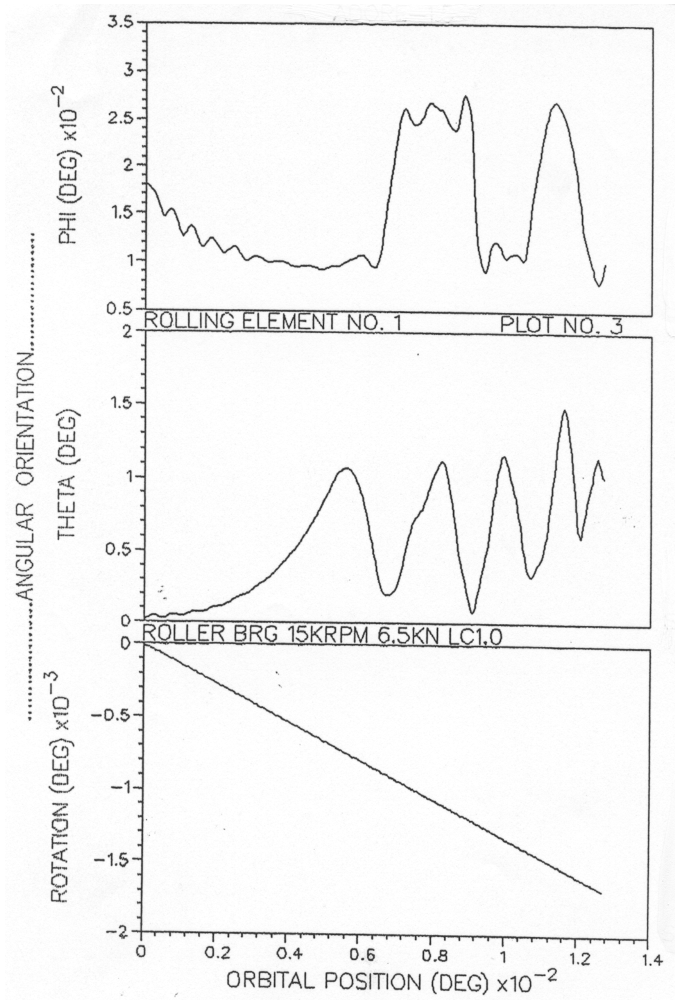
ADORE Examples

Roller Skew with Off Centered Land



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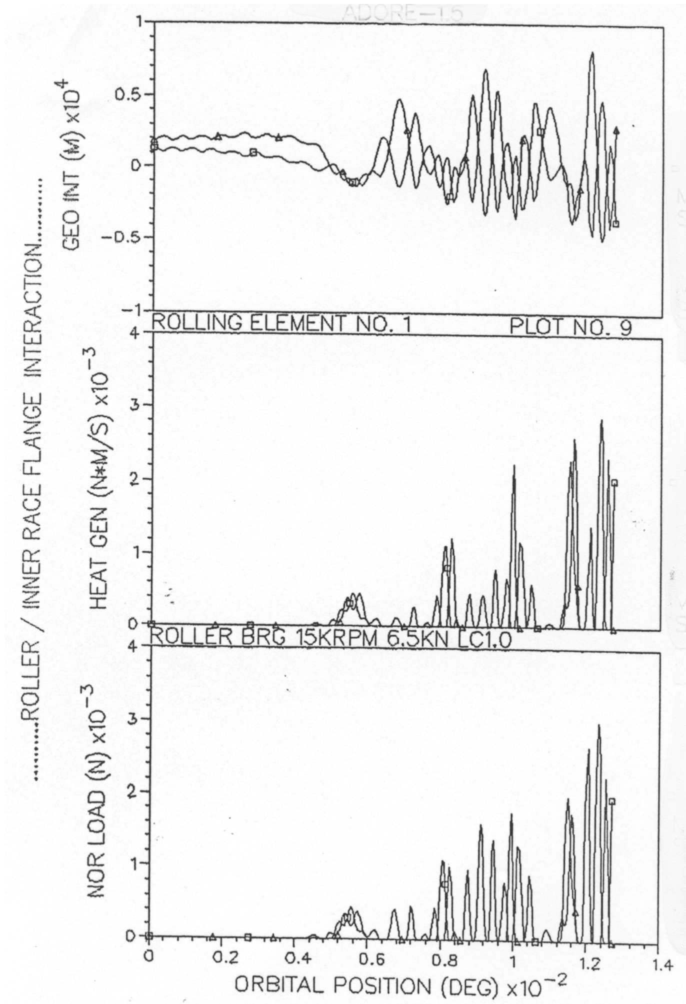
ADORE Examples

Flange Interaction with Off Centered Land



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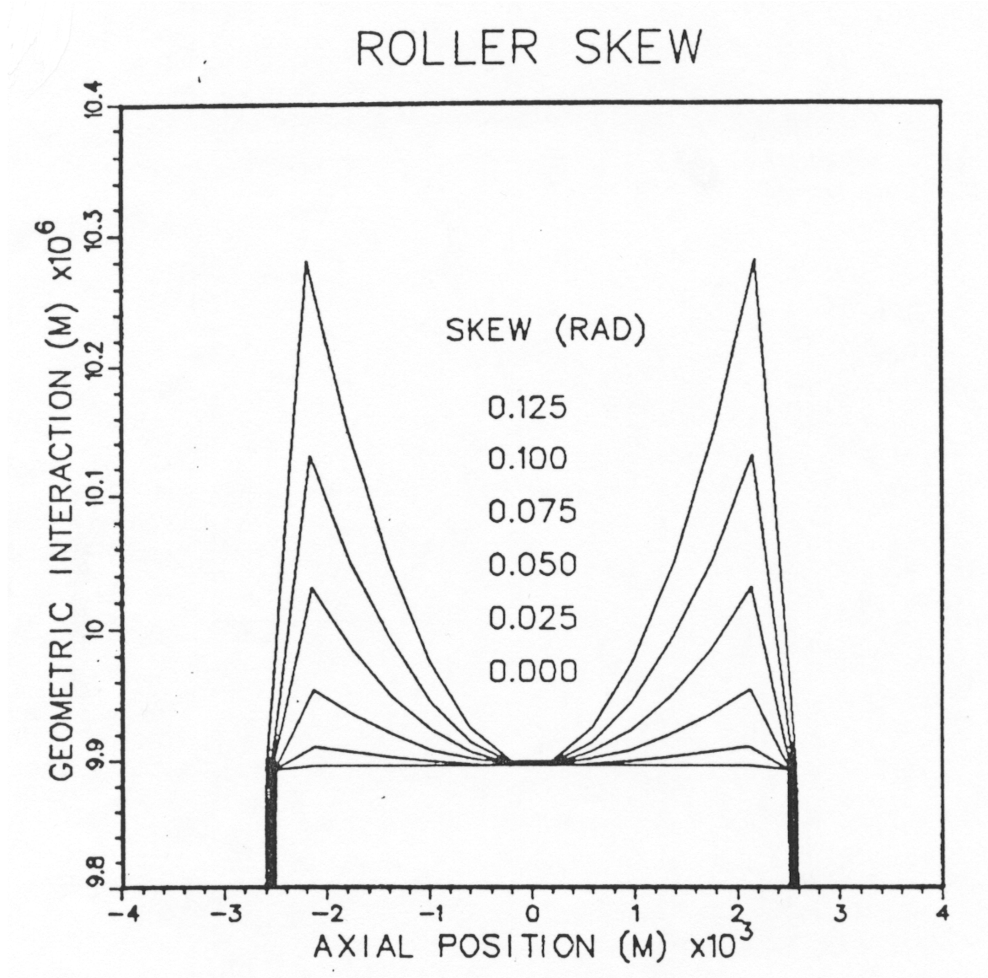
ADORE Examples

Load Distribution under Excessive Roller Skew



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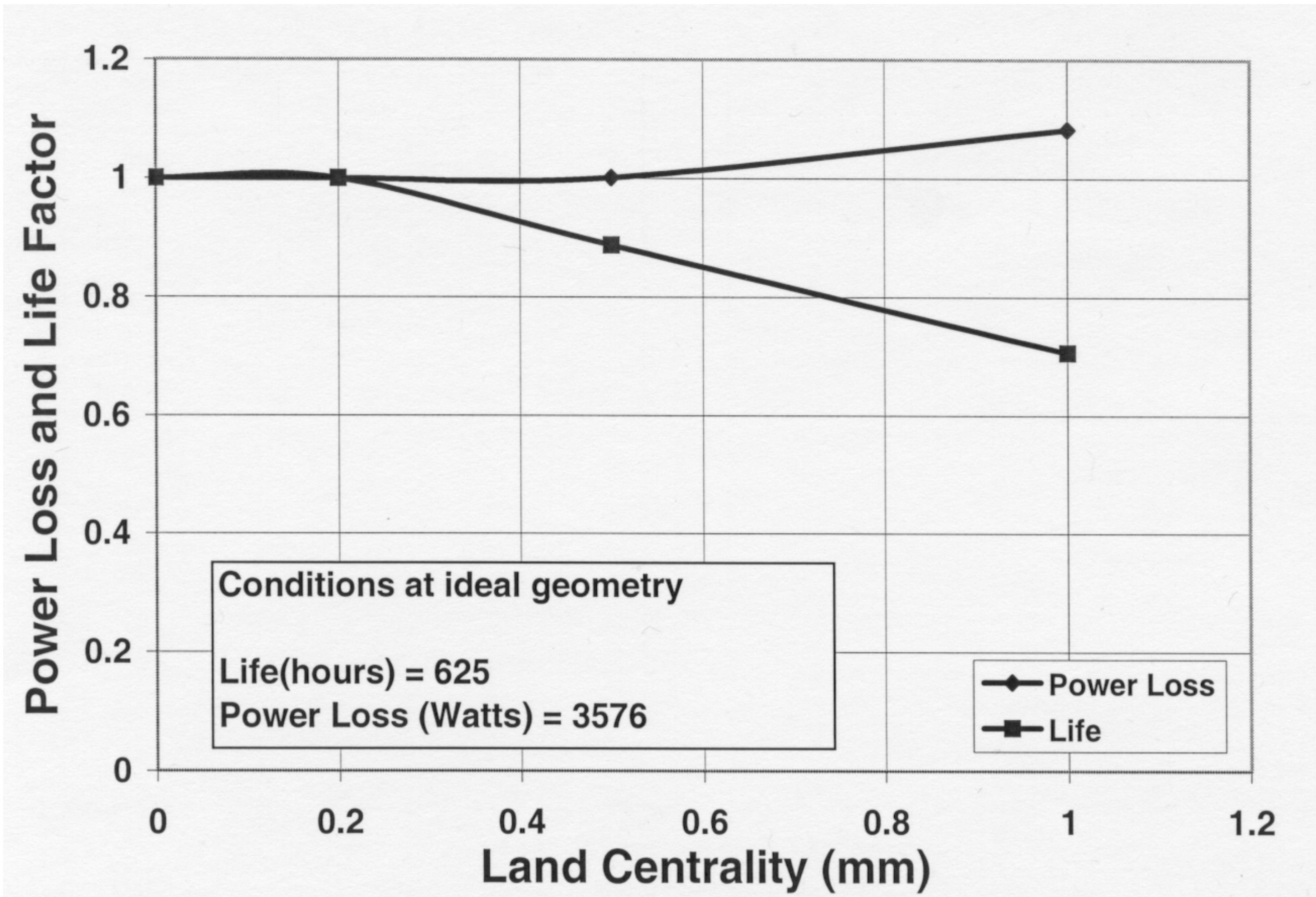
ADORE Examples

Overall Effect of Off Centered Land



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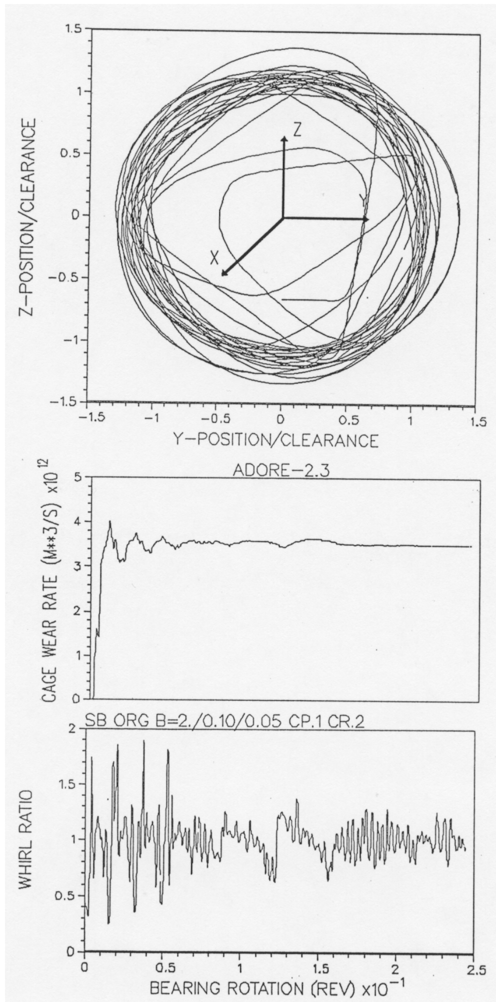
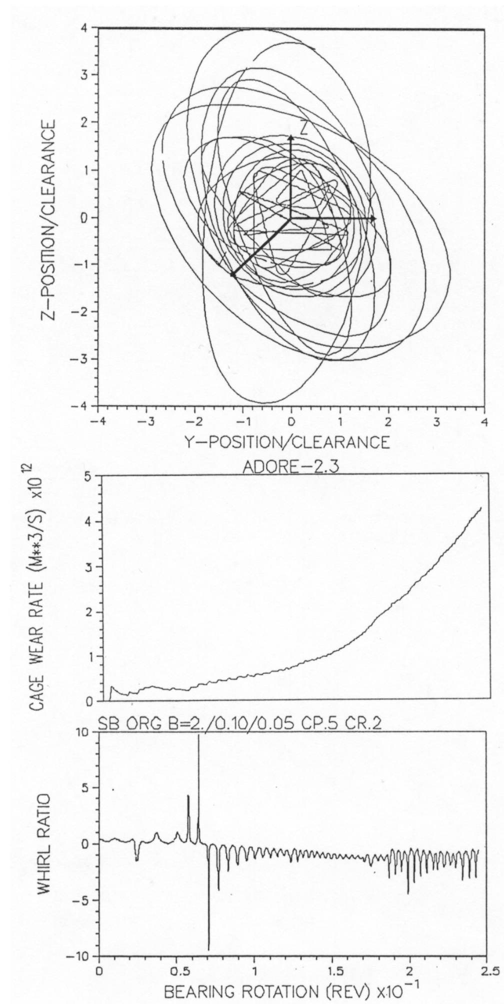
ADORE Examples

Cage Whirl Instability with Increasing Pocket Clearance





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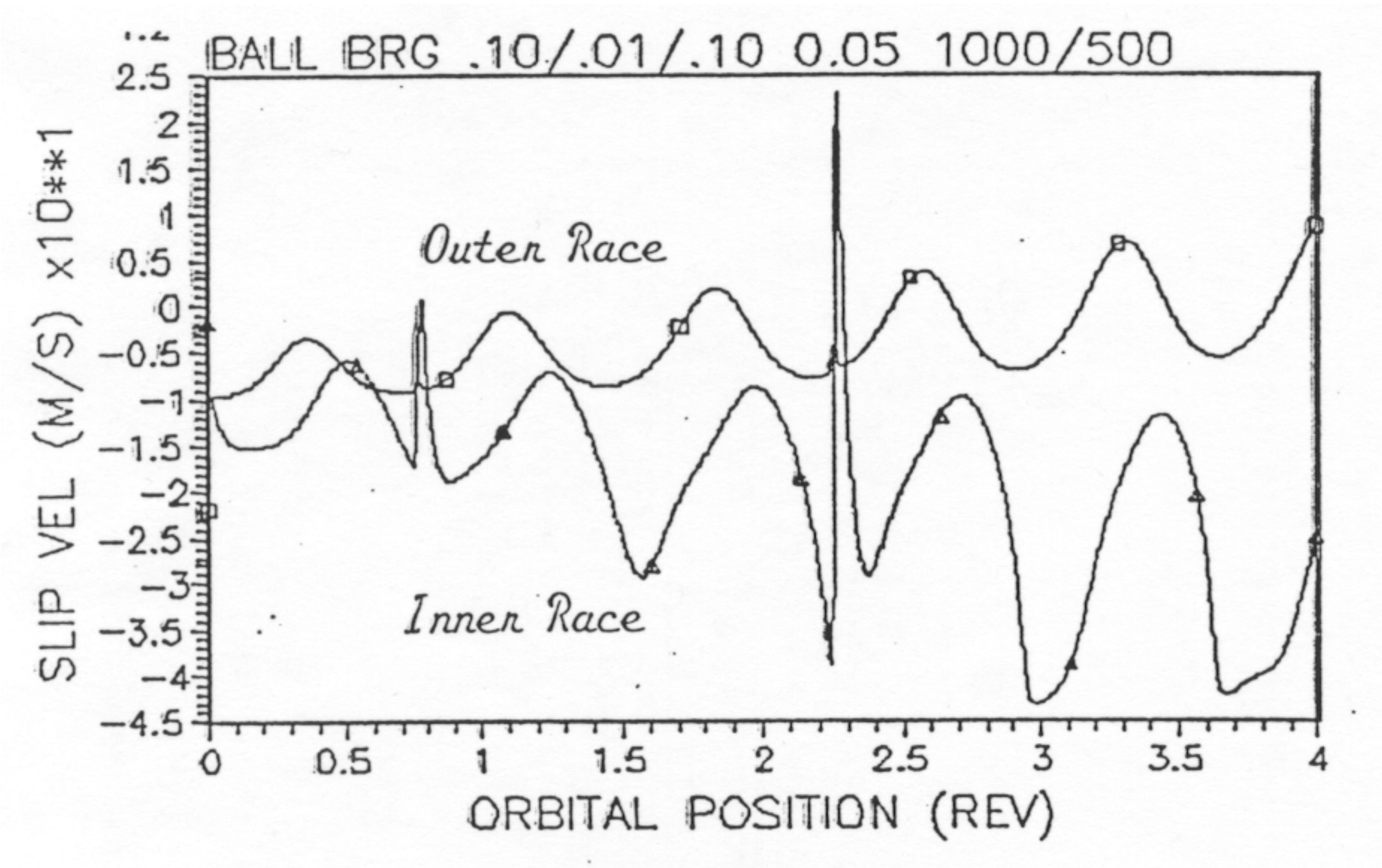
ADORE Examples

Pocket Interaction under Skid Instability



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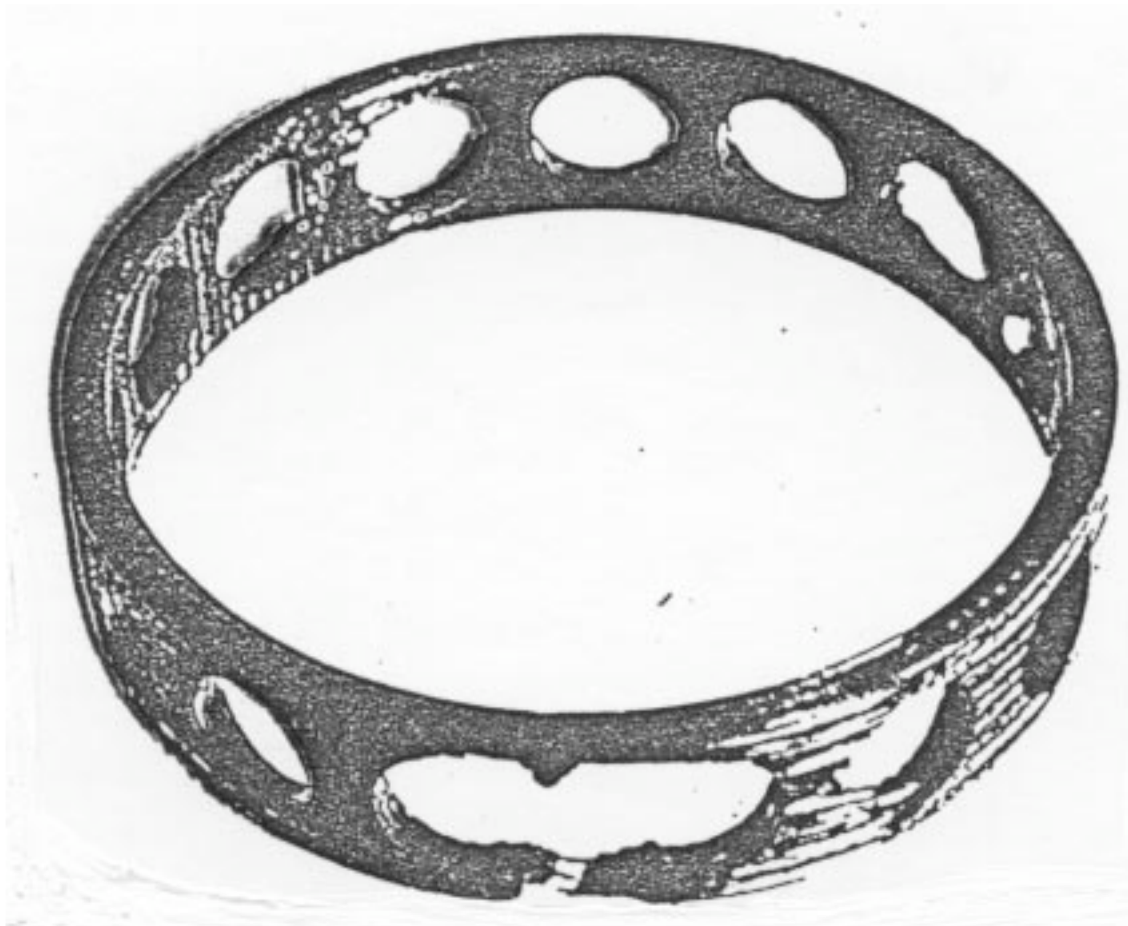
ADORE Examples

Cage Damage under Skid Instability



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