ADORE

Advanced Dynamics Of Rolling Elements

Technical Seminar

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ADORE Technical Seminar

- User Training Seminar

  Part 1: Program Description and Capabilities

  Part 2: Input Data and File System Management

  Part 3: Program Output and User Applications
- Recommendations for Addition Technical Support

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

- Introduction
- Development Fundamentals

  Break

- ADORE Overview
- Interaction Models

  Break

- Numerical Considerations
- Experimental Validation

  Break

- Examples
- Discussion

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- ADORE Input - Program Input and Control

  Break

- ADORE Input - Bearing Geometry
- ADORE Input - Material Properties
- ADORE Input - Operating Conditions

  Break

- ADORE Input - Frictional Interactions
- Optional Input to Graphics Module
- Data File Management

  Break

- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

  Break

- Critical Performance Parameters
- Computing effort optimization
- Summary
- Discussion

  Break

- User Applications and General Discussion

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Part 3: Program Output and User Applications

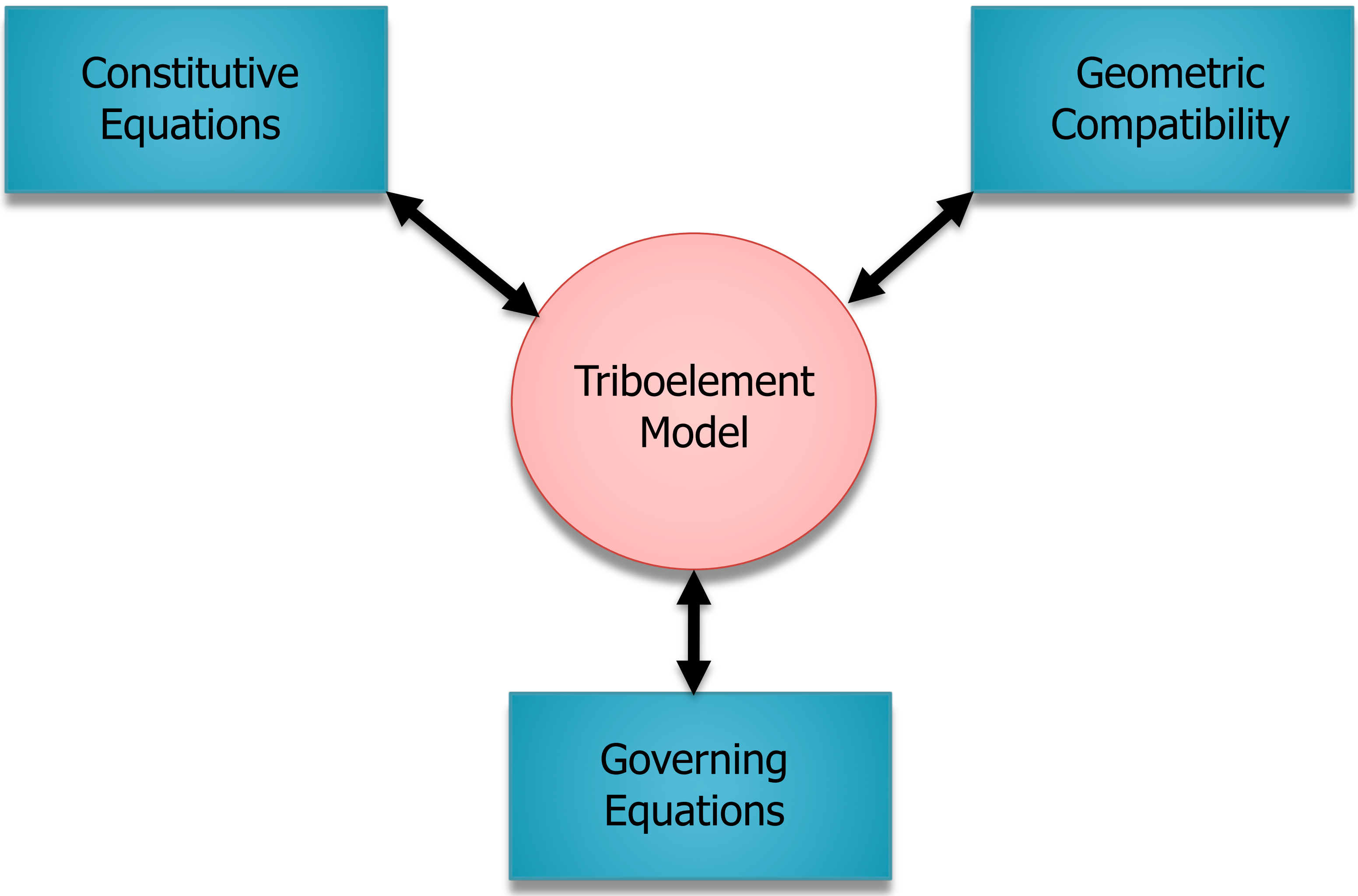
Introduction
Fundamentals of Model Development

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

Introduction
Modeling Fundamentals

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

Introduction
Model Components



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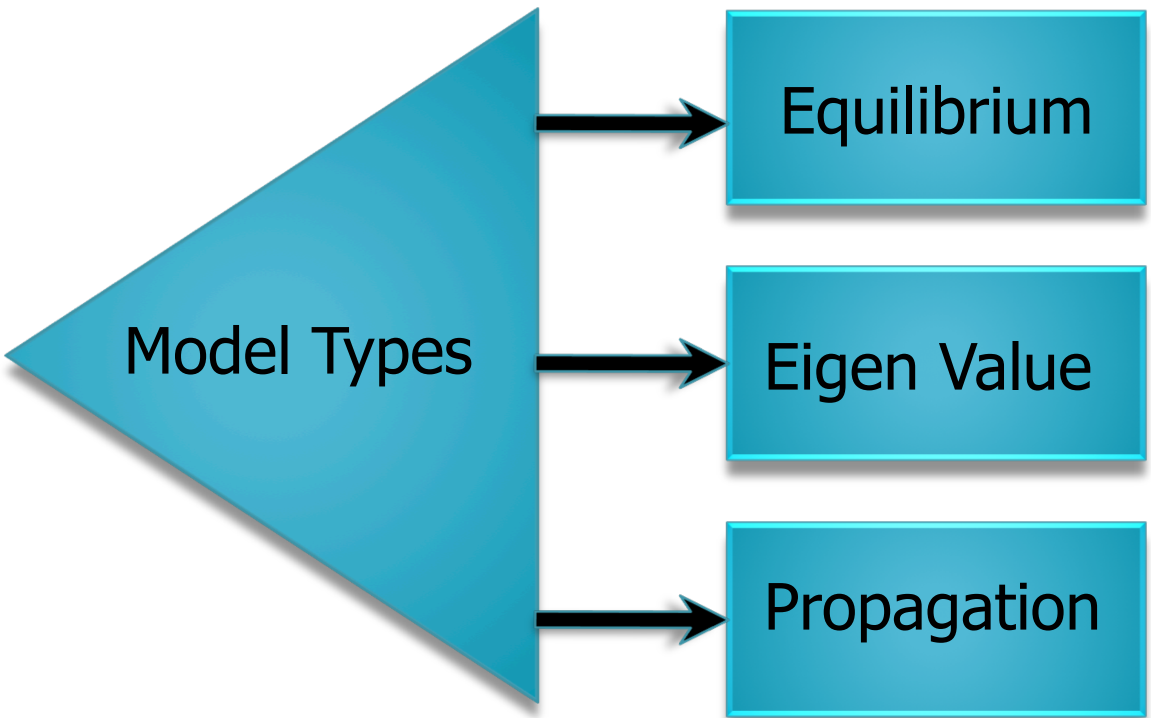
Introduction

Model Types

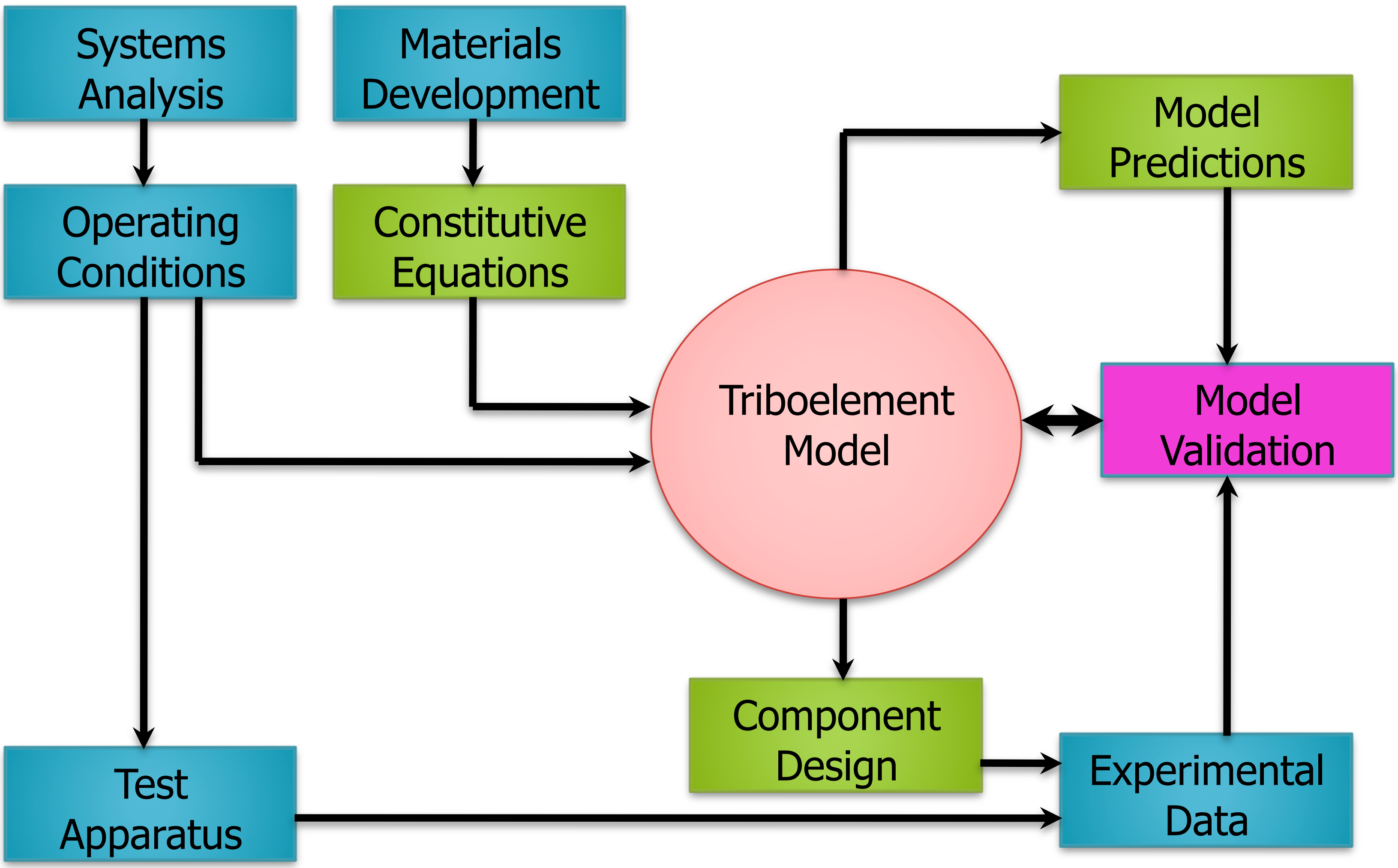


$$\sum F = 0$$
$$\sum G = 0$$

$$AX = \lambda BX$$

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

Introduction
Model Development Process



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Introduction

Evolution of ADORE

- Need for real-time performance simulation
- Lubricant behavior
- Dynamic bearing failures
- Analytical formulations of basic interactions
- Experimental support
- Model integration

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Development Fundamentals
Types of Rolling Bearing Models

- Quasi-Static models

$$\sum F = 0$$

$$\sum G = 0$$

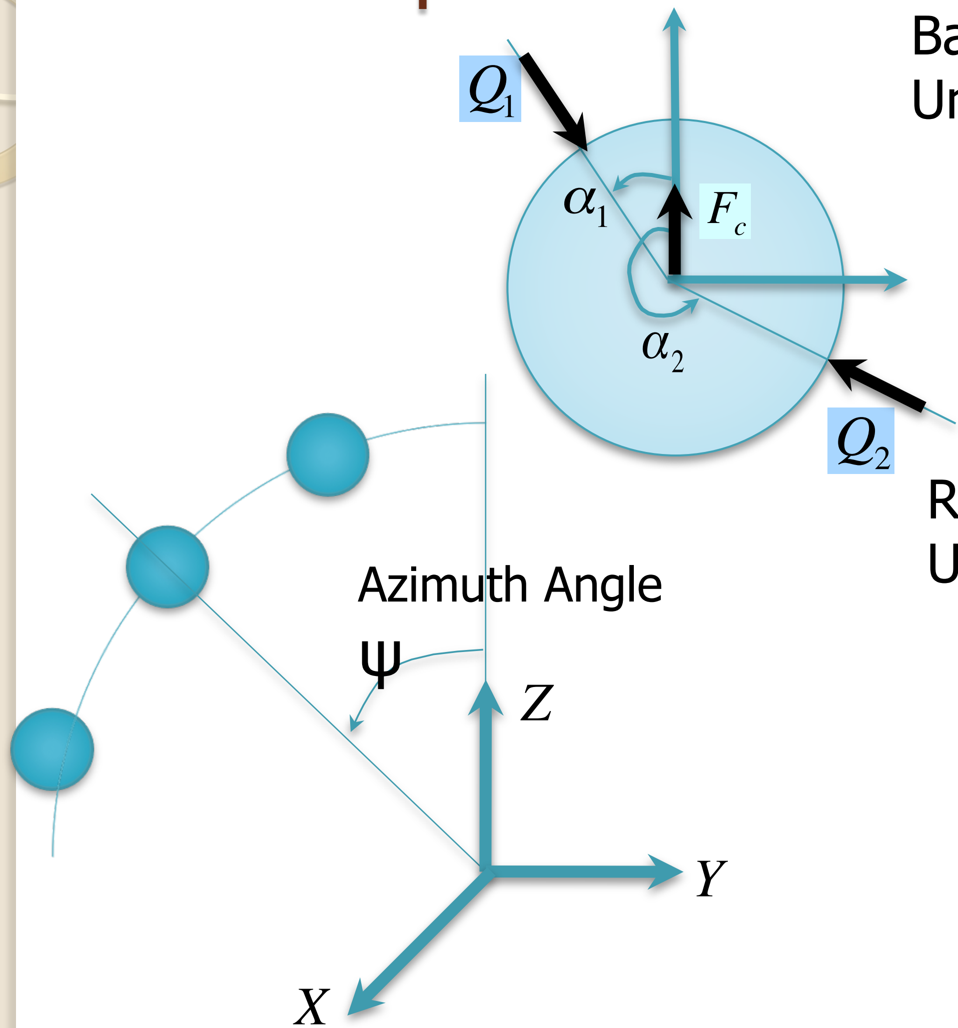
- Dynamic models

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

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

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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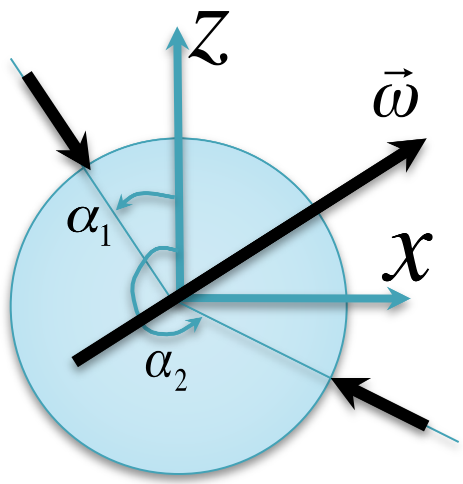
Development Fundamentals

Ball Angular Velocities



Unknowns:

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

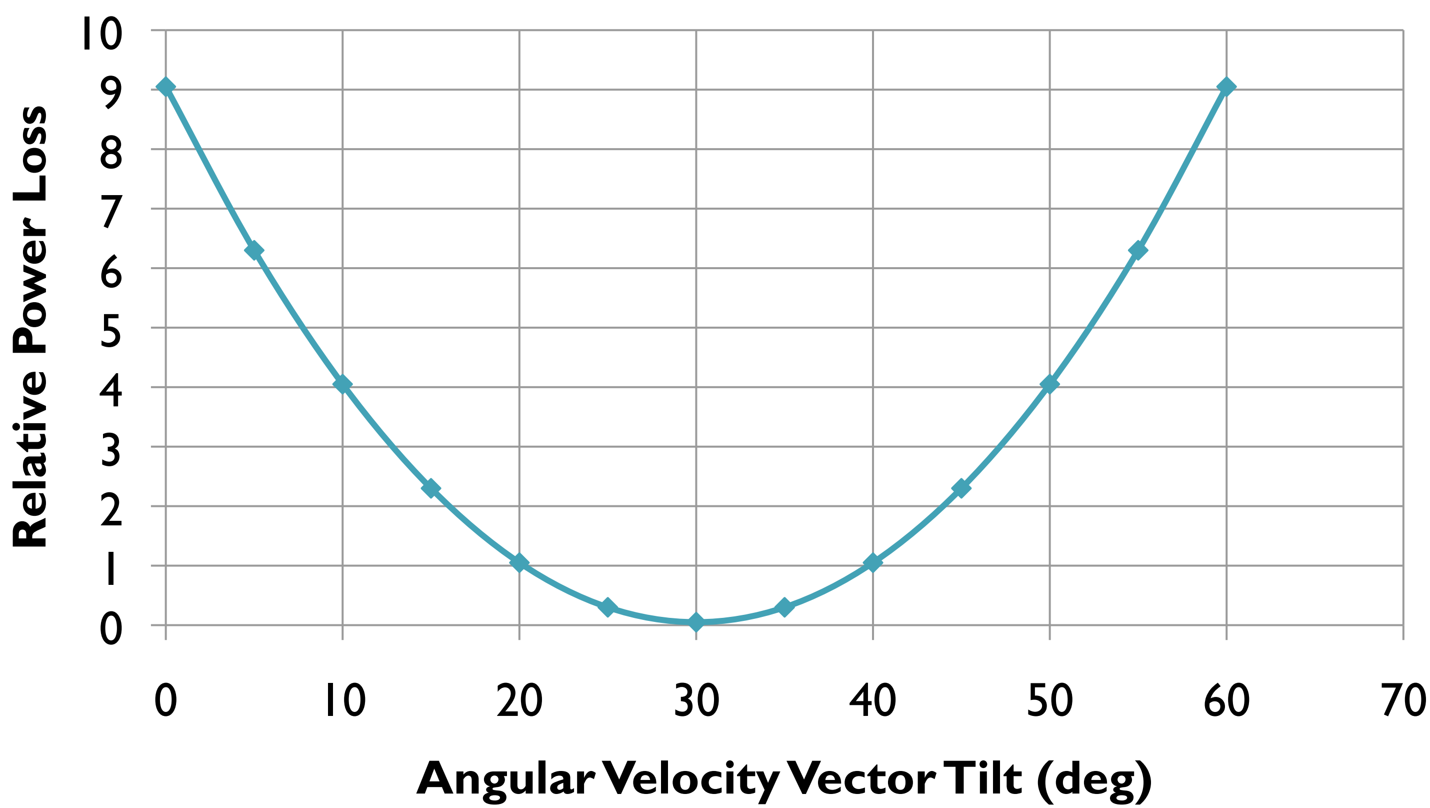
Available Equations:

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

Third Equation?

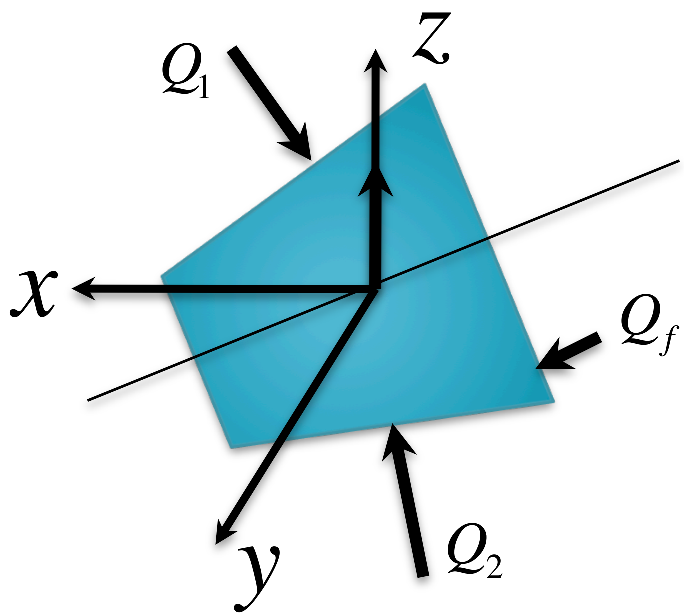
- Arbitrary angle – generally used in roller bearing
- Race Control – based on friction torques in race contacts
- Minimize energy in race contacts – new in ADORE

Development Fundamentals
Minimum Energy Constraint



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

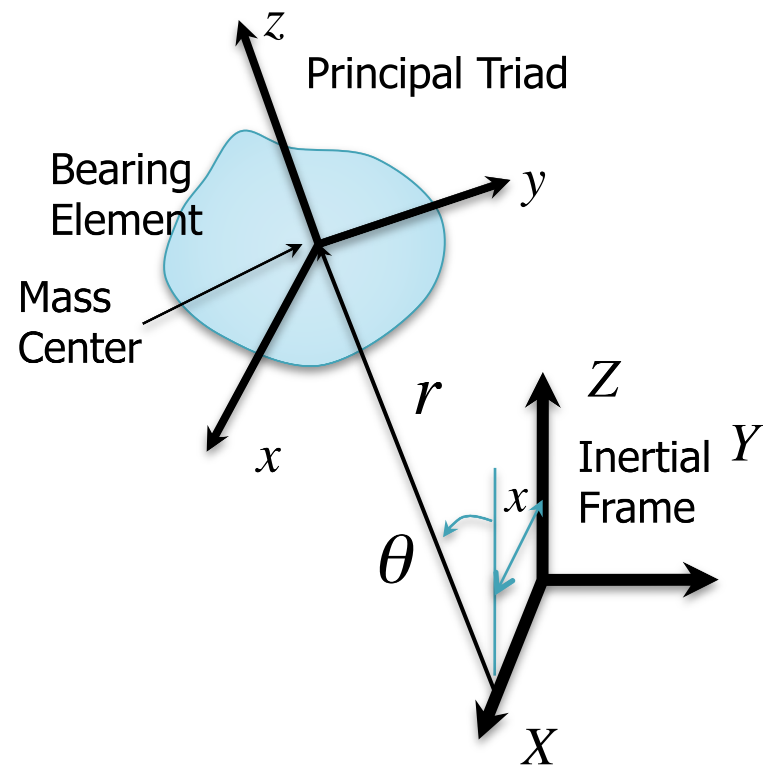
Moment Equilibrium: $M_{y_1} + M_{y_2} + M_{y_f} + G_y = 0$

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

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 Technical Seminar

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- Interaction Models

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- Numerical Considerations
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ADORE Overview

- Development time line
- Generalized dynamics model
- Complete six-degrees-of-freedom system
- Highly modular structure
- Performance simulation and design tool
- Current distribution and applications

ADORE Overview
Development Time Line

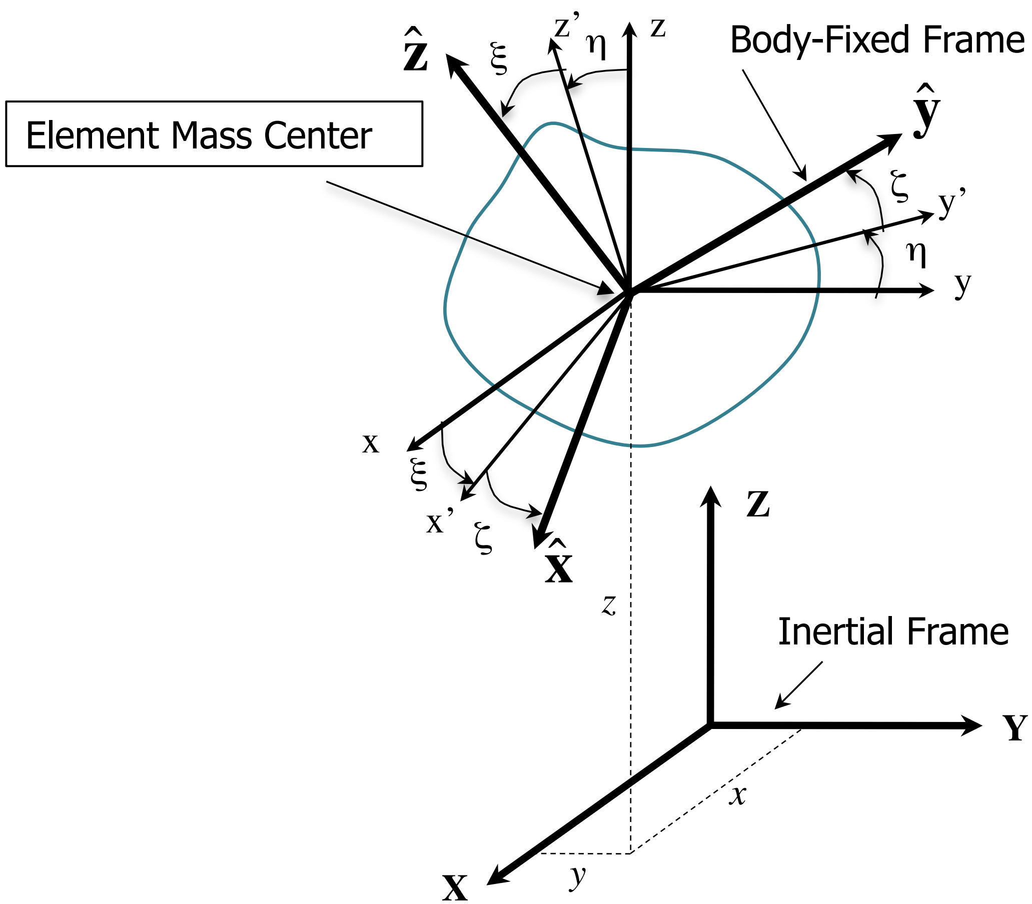
Time Range	ADORE Related Development
1971-75	Fundamental Development
1976-77	Fully dynamics model for both ball and roller bearings
1978-82	Advancements in numerical methods
1982-83	Geometrical generalizations, tapered and spherical bearings
1984	First publication of ADORE
1985-86	Manufacturing tolerances, 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

ADORE Overview

Generalized Six-Degrees-of-Freedom



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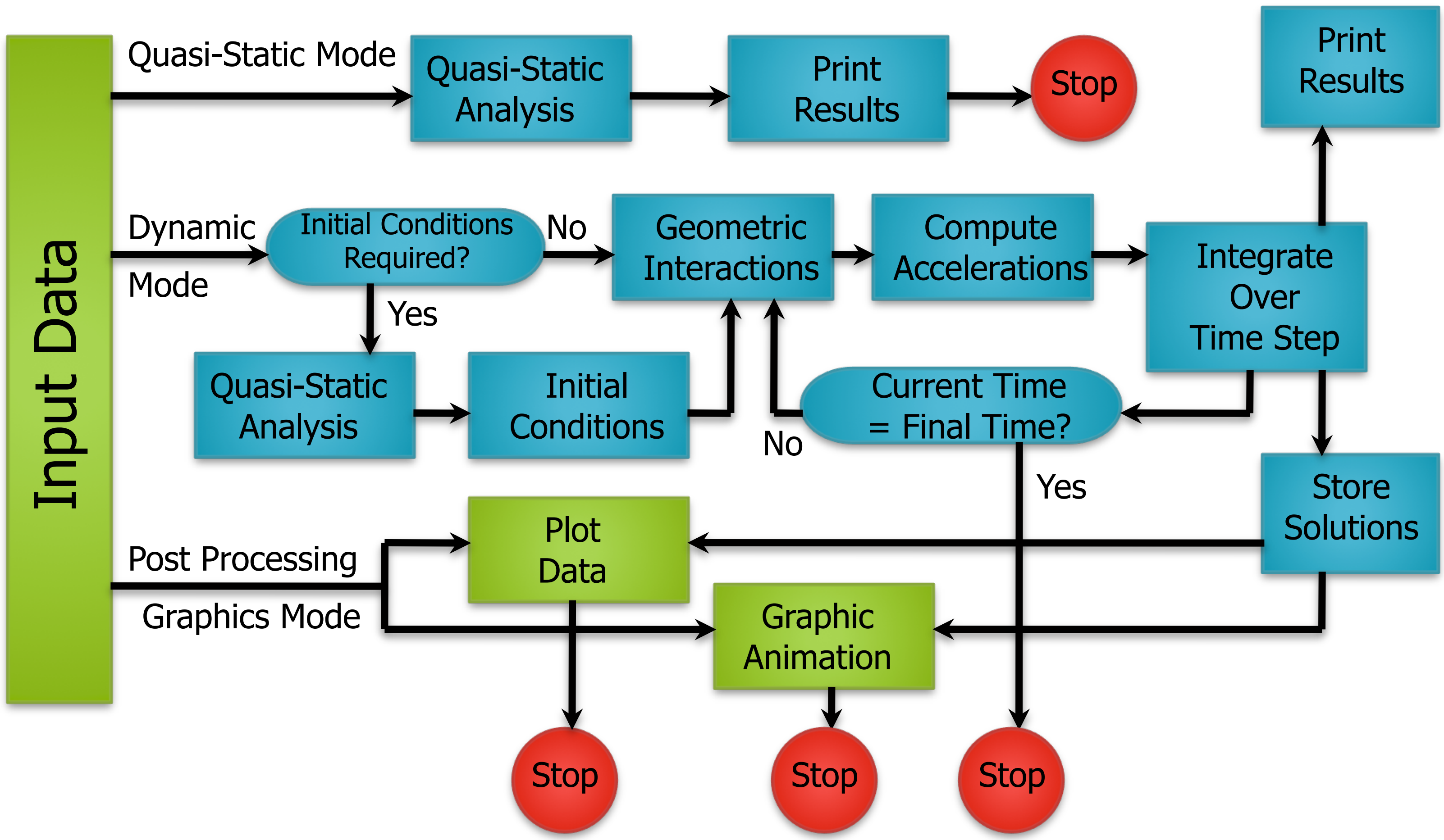
ADORE Overview
Simplified Flow Chart



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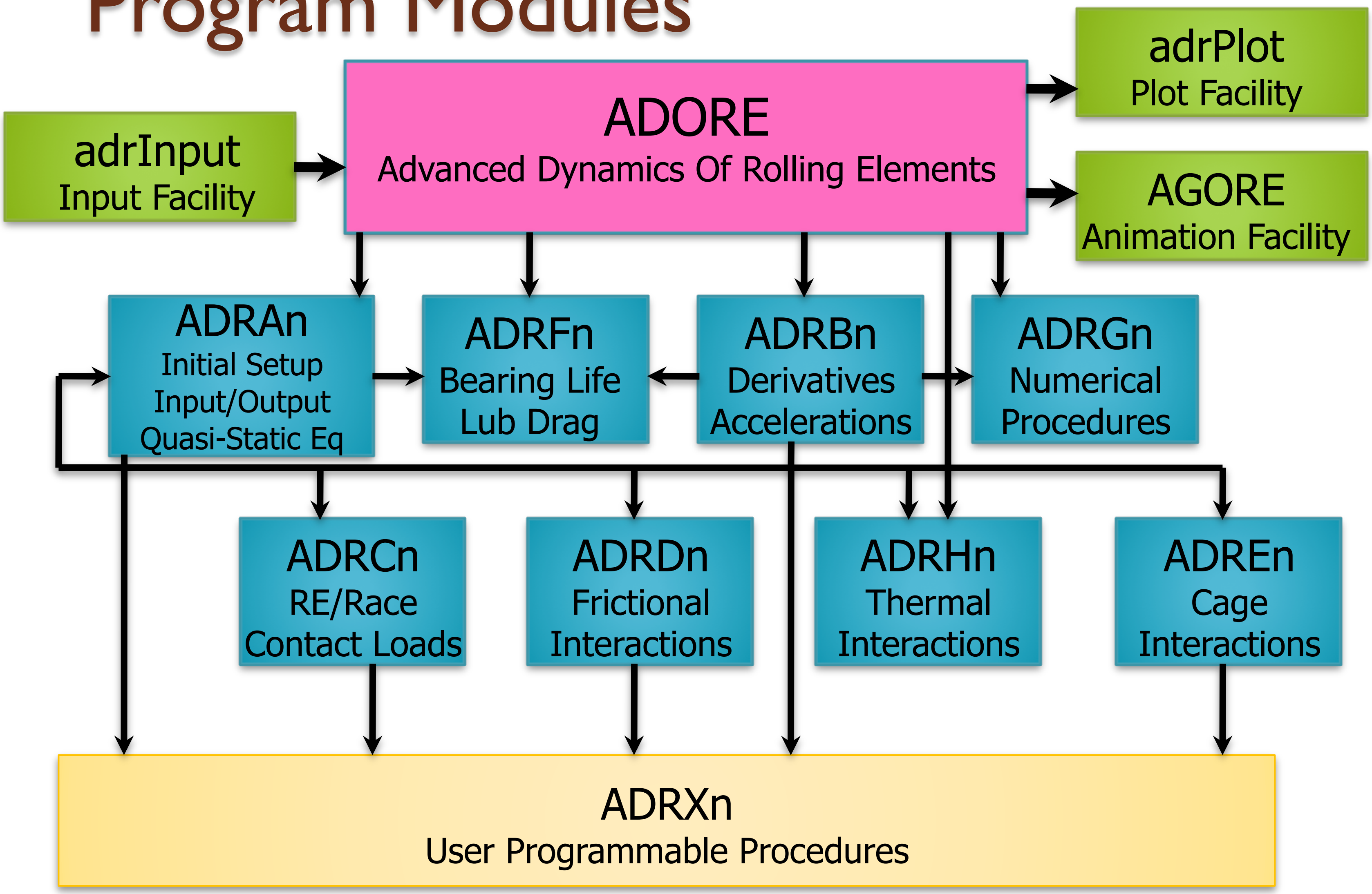
ADORE Overview
Program Modules



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

Performance Simulation and Design Tool

- 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

Performance Parameters

- Bearing fatigue life
- Stiffness
- Overall heat generation or power loss
- Stability of bearing element motion
- Wear

ADORE Overview

Current Distribution

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

ADORE Overview

Notable Applications

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

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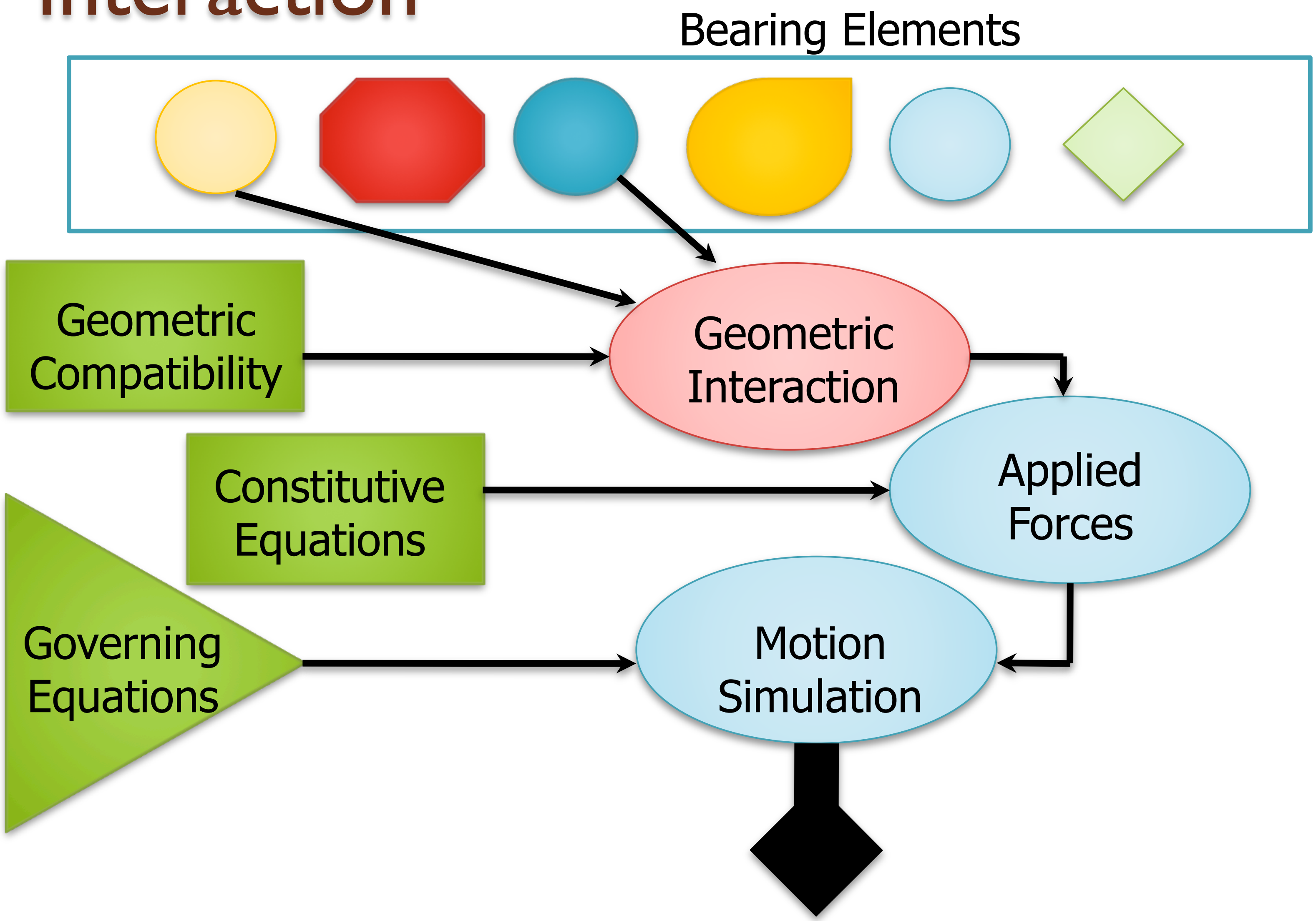
Fundamentals of Bearing Element Interaction



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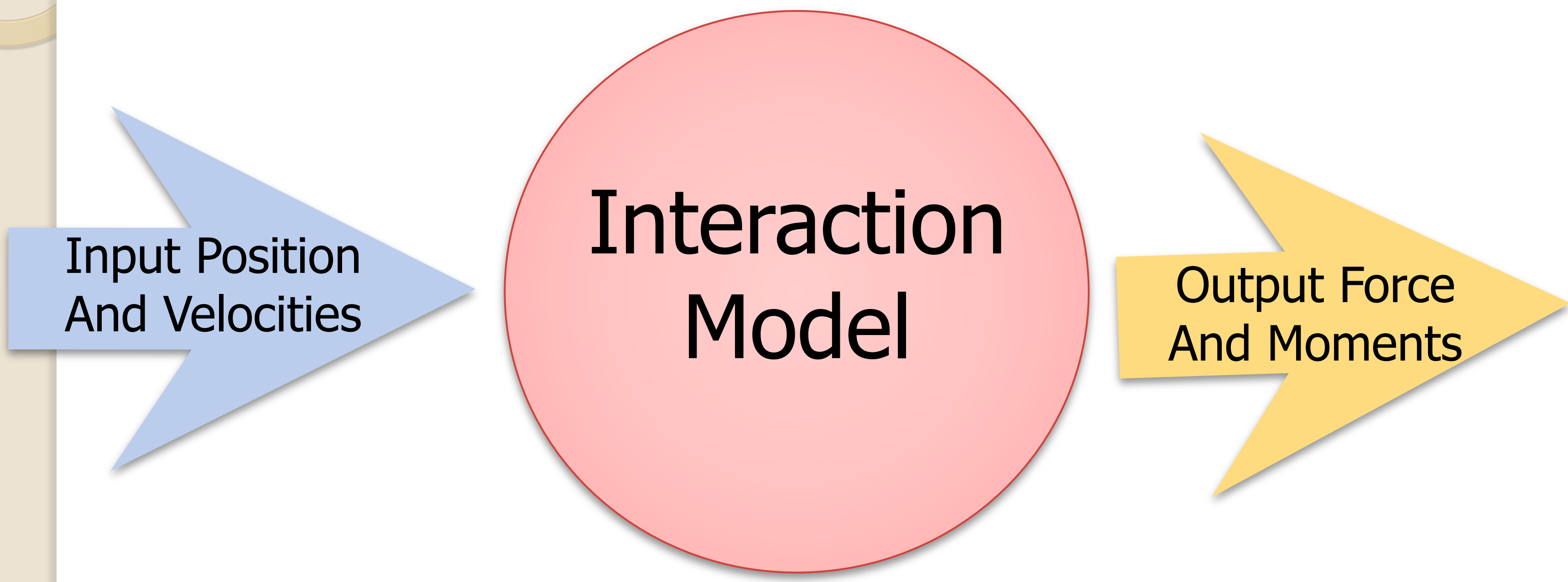
Interaction Model



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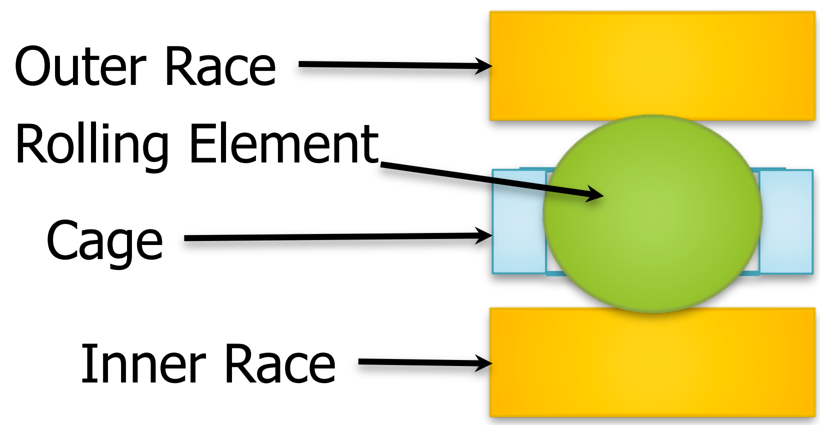
Elements of a Rolling Bearing

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



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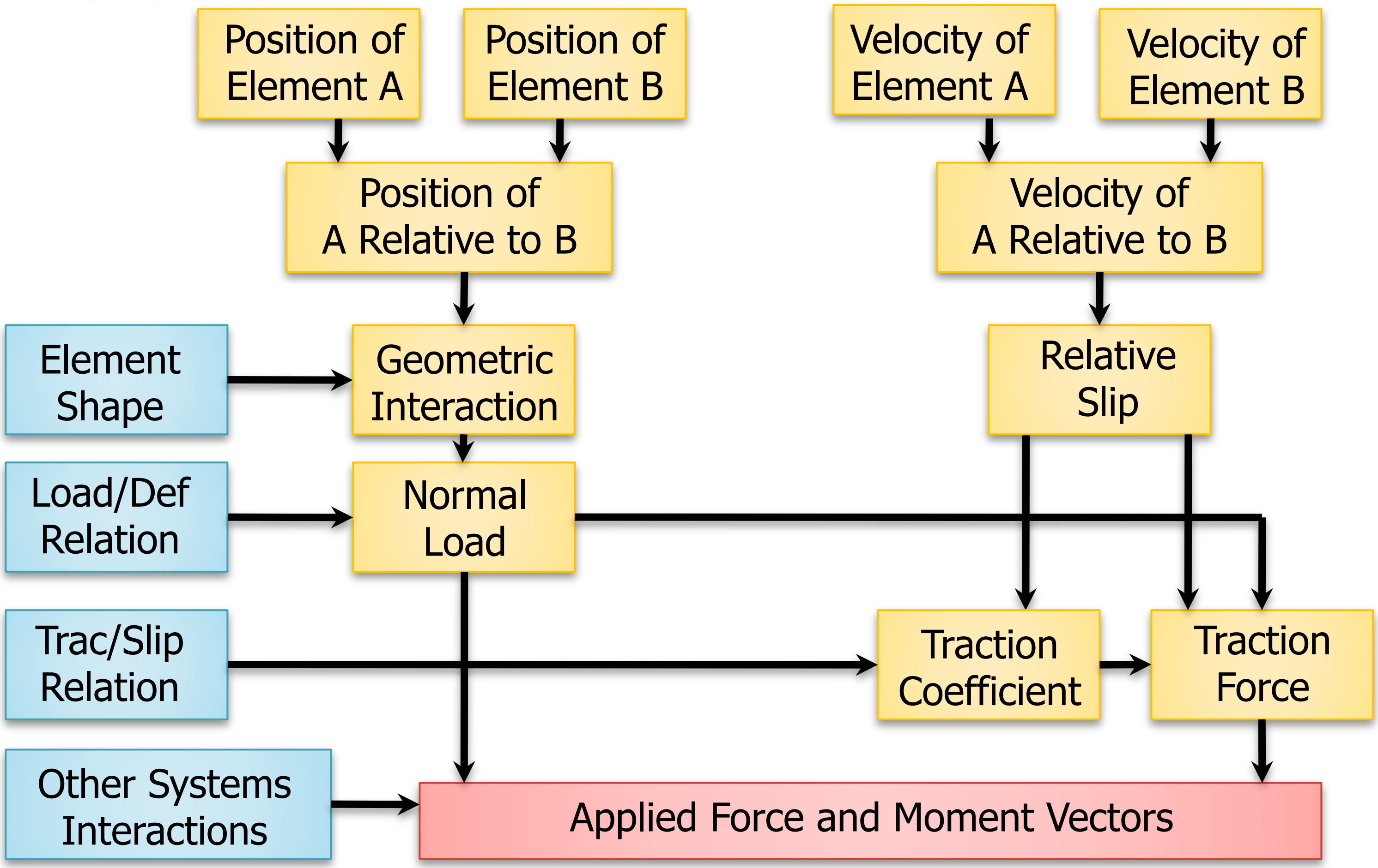
Generic Architecture of Interaction Models



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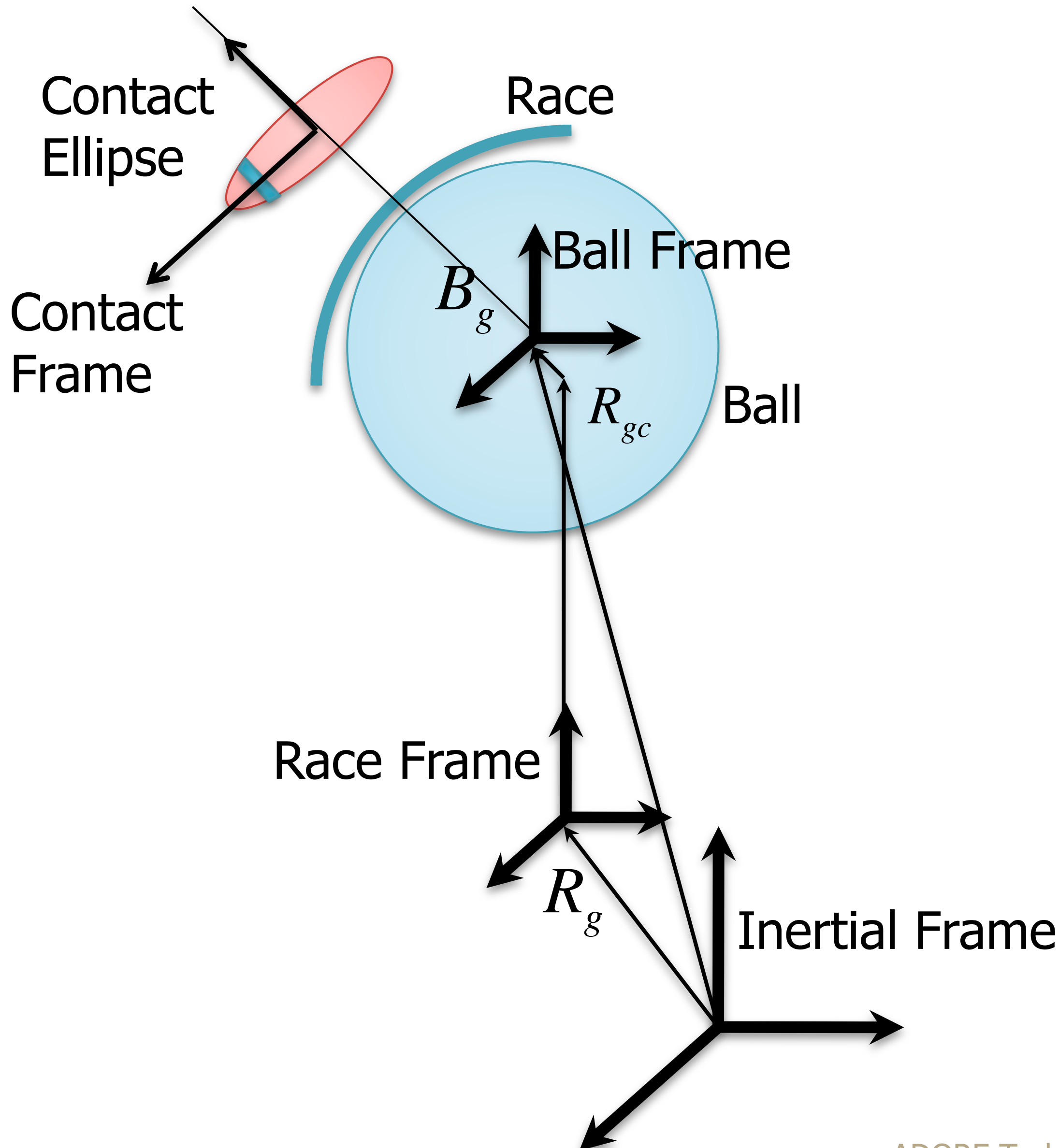
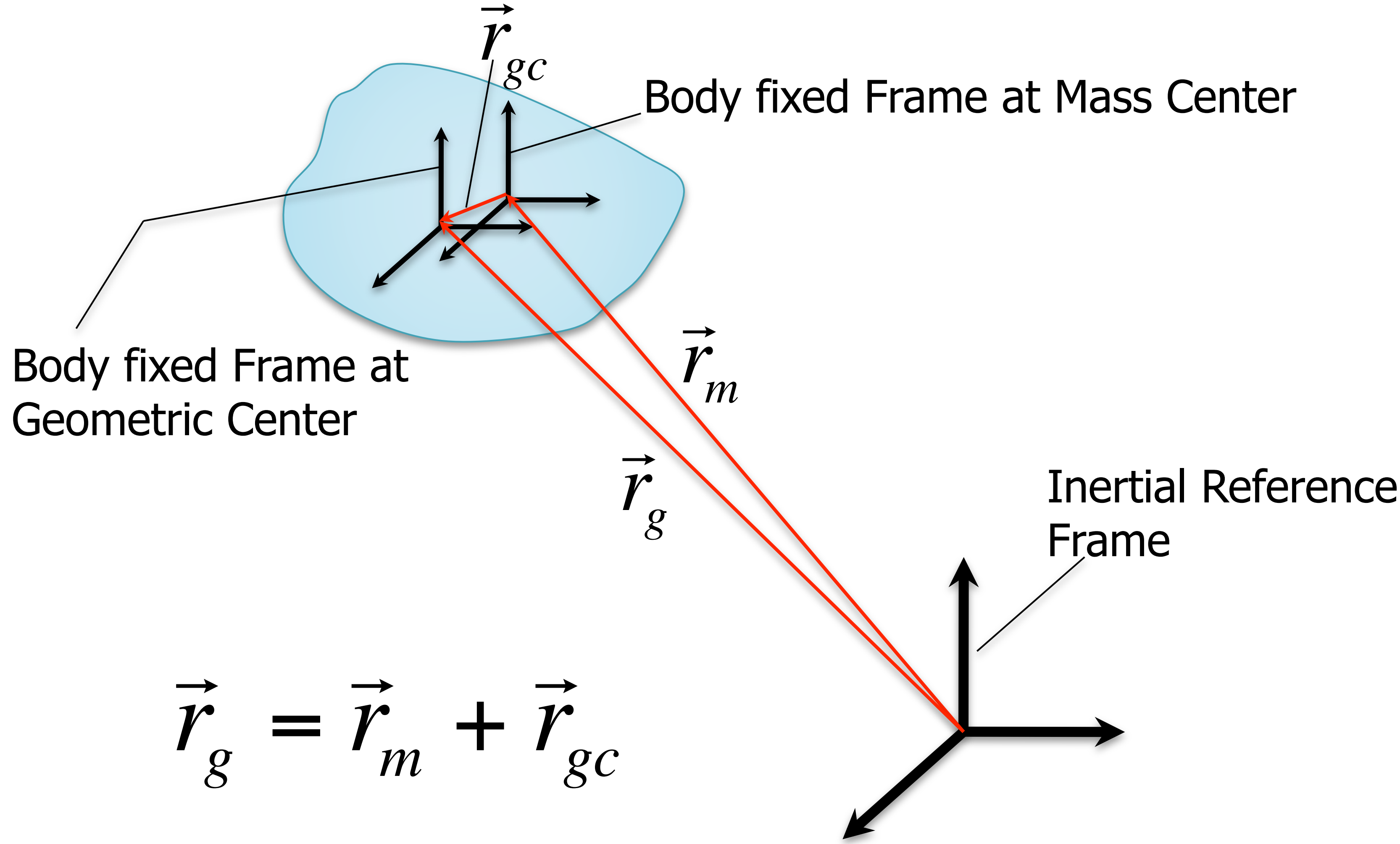
Ball-Race Interaction



Mass to Geometric Center



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

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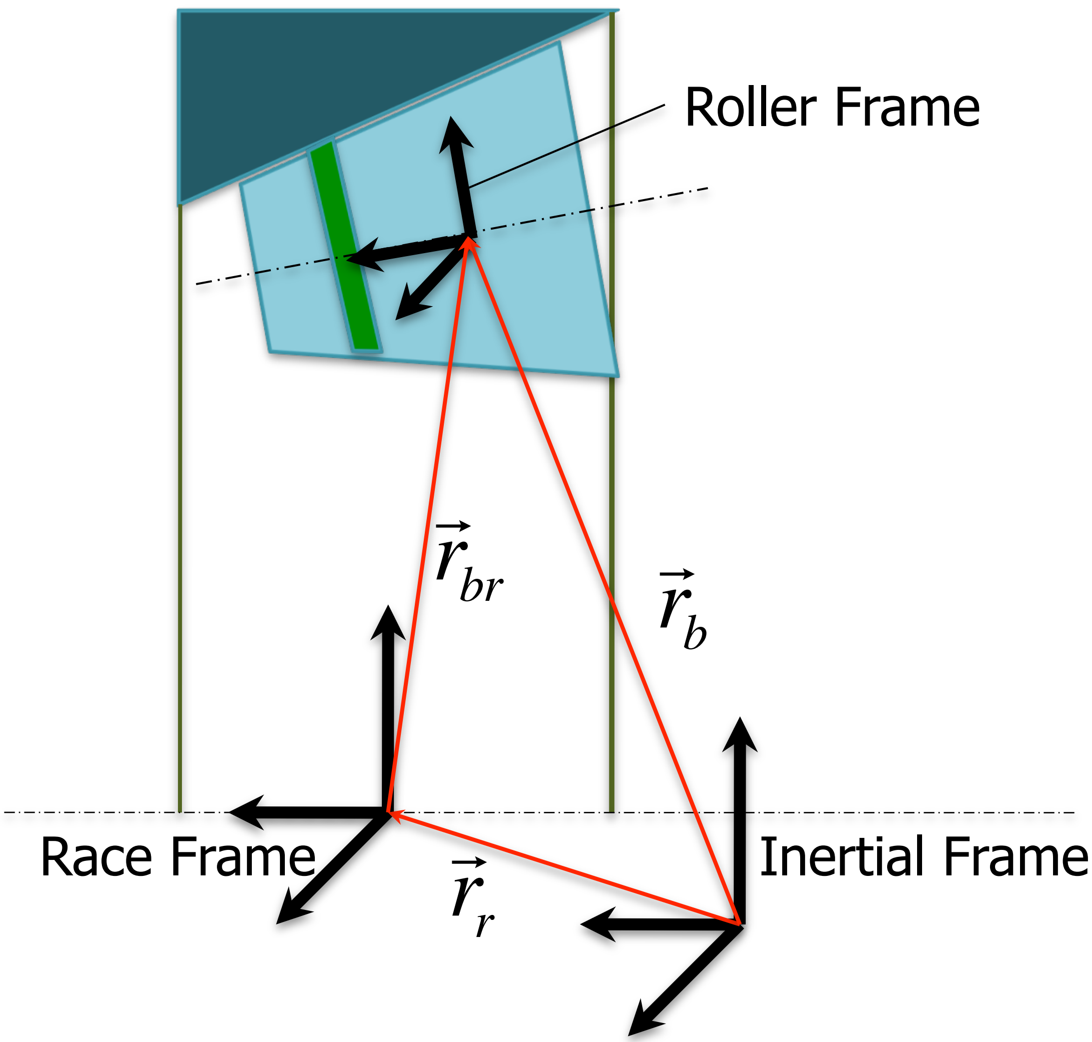
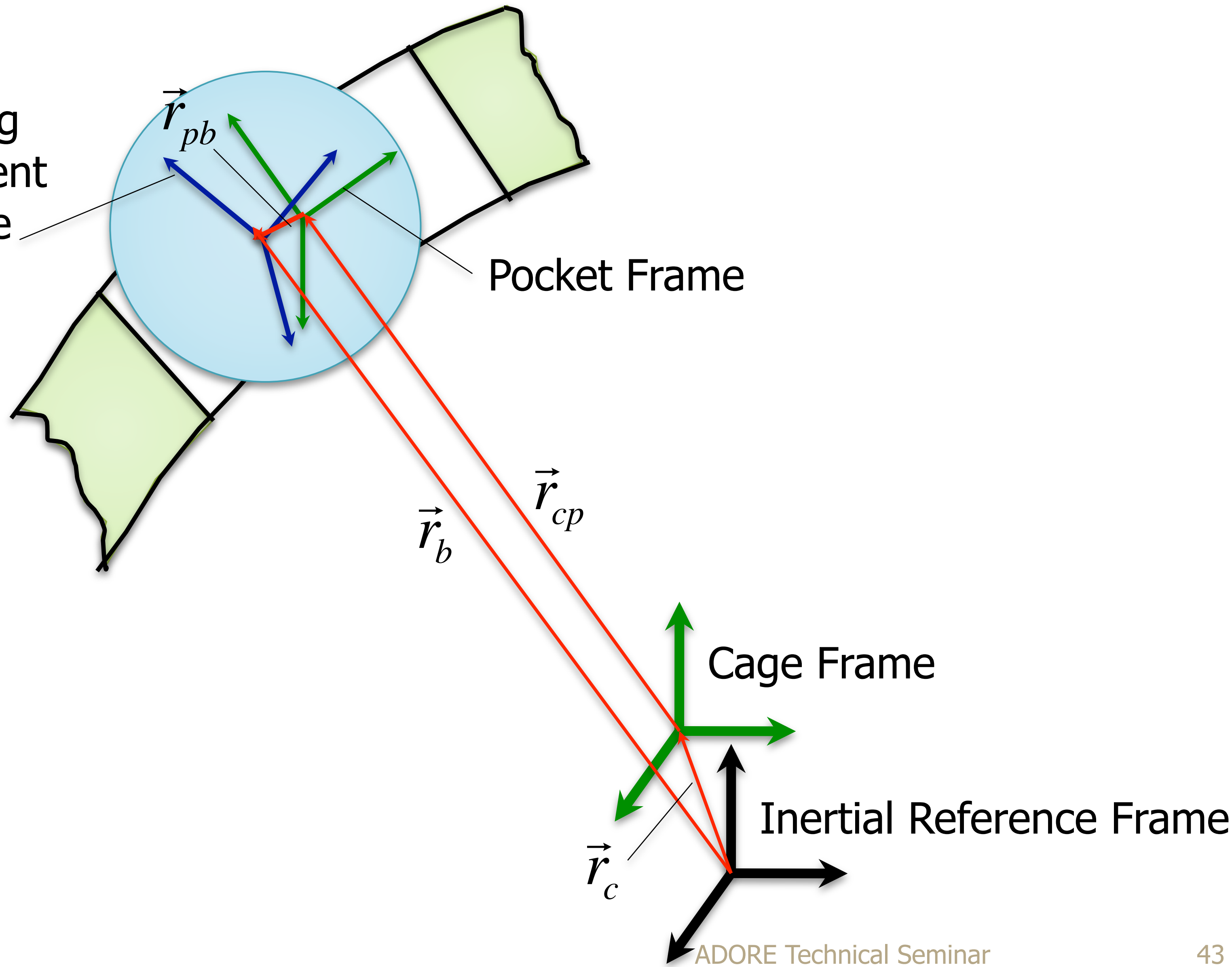
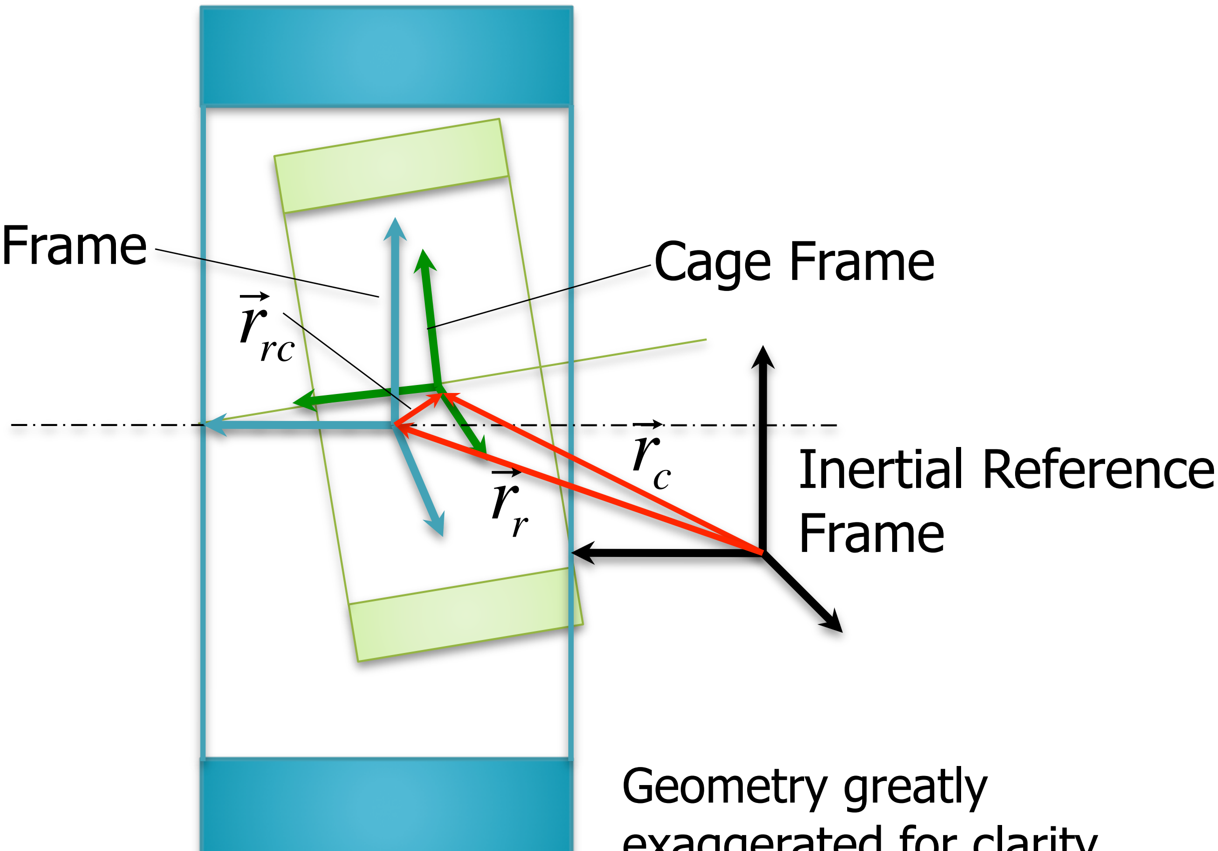
Roller Race Interaction



Rolling Element to Cage Interaction



Cage to Race Interaction



Geometry greatly exaggerated for clarity

Other External Interactions and Constraints

- Churning and drag
- Other external forces, e.g. fluid flow through the bearing
- Displacement constraints on races
- Time varying loads and speeds
- Other application specific interactions

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Numerical Considerations

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

Numerical Considerations

Dimensional Organization

- Numerical round-off and truncation
- System of units
- Large versus small bearings
- ADORE Scales
  - Force = Largest load on the bearing
  - Length = Rolling element radius
  - Time = Wave length of highest frequency
- All scales computed during data setup
- Series expansion to avoid errors

Numerical Considerations

System of First Order Differential Equations

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

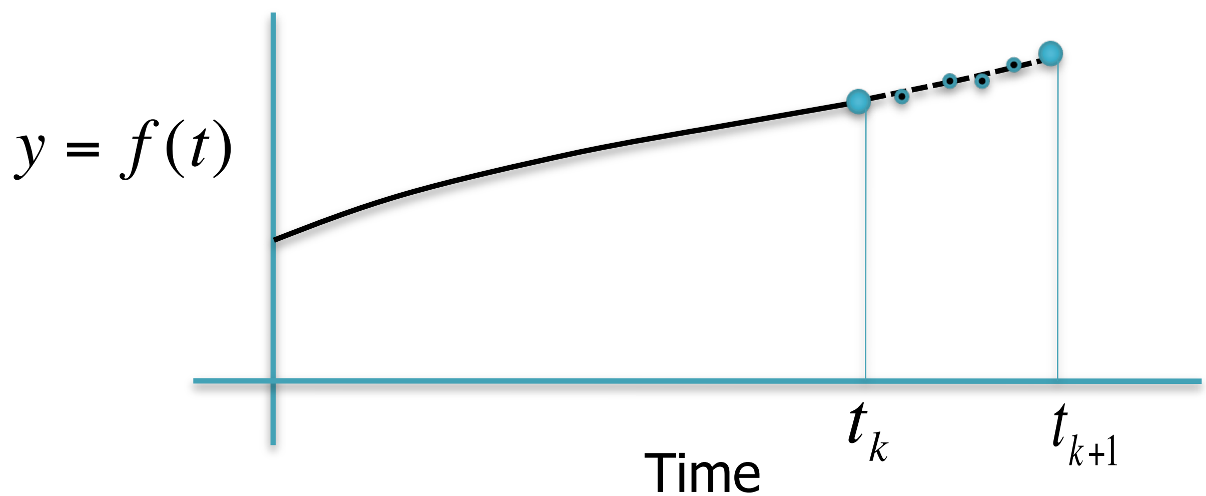
$$m\ddot{x} = F \Rightarrow \begin{array}{l} m\dot{v} = F \\ \dot{x} = v \end{array}$$

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

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



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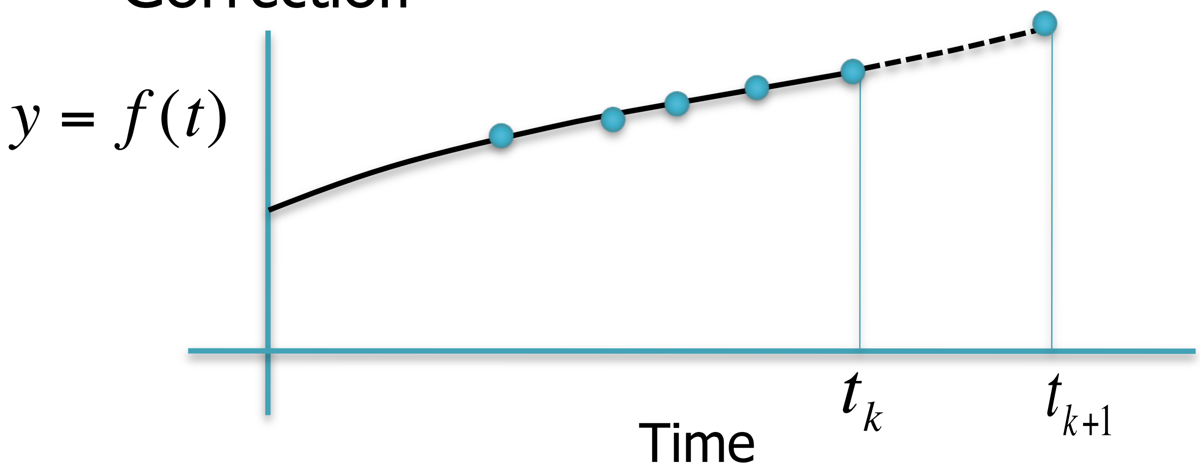
Numerical Considerations

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 sense 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

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

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

- ADORE arbitrarily sets

$$\alpha = 0.80$$

Numerical Considerations

Step Size Optimization

- When actual truncation error is larger than the prescribed limit ADORE first checks for any discontinuity such as cage contact
- In the event a new cage contact does come into existence then the contact frequency is computed and step size is reduced to one quarter the wave length and the integration is attempted again
- If no discontinuity is present the step size is appropriately reduced

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

- The step size thus varies continually between the prescribed limits

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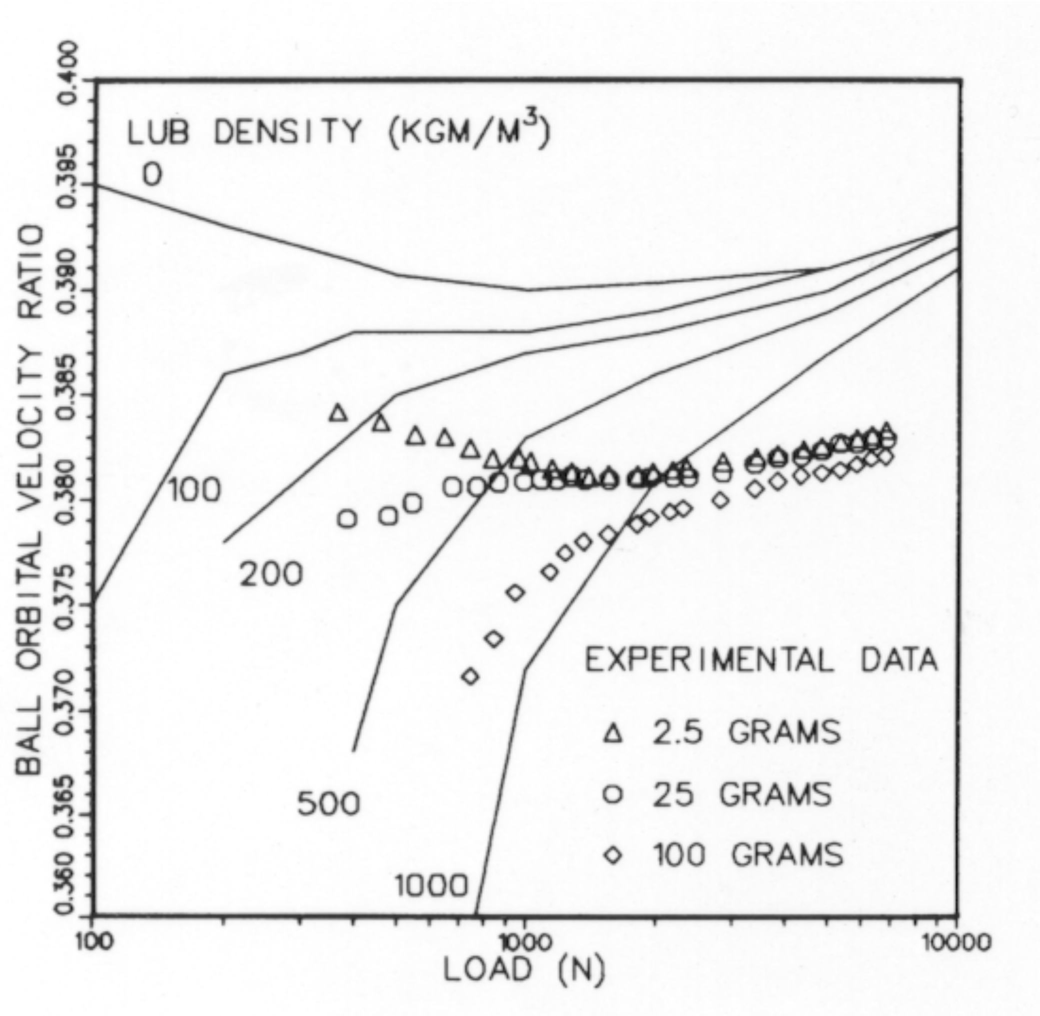
ADORE Experimental Validation

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

ADORE Experimental Validation
Field Experience

- Large number of varied applications
- Observed performance duplicated with ADORE simulations
- Critical parameters identified
- Parametric evaluation to determine fix
- Predicted fix successfully implemented

ADORE Experimental Validation
Ball Skid



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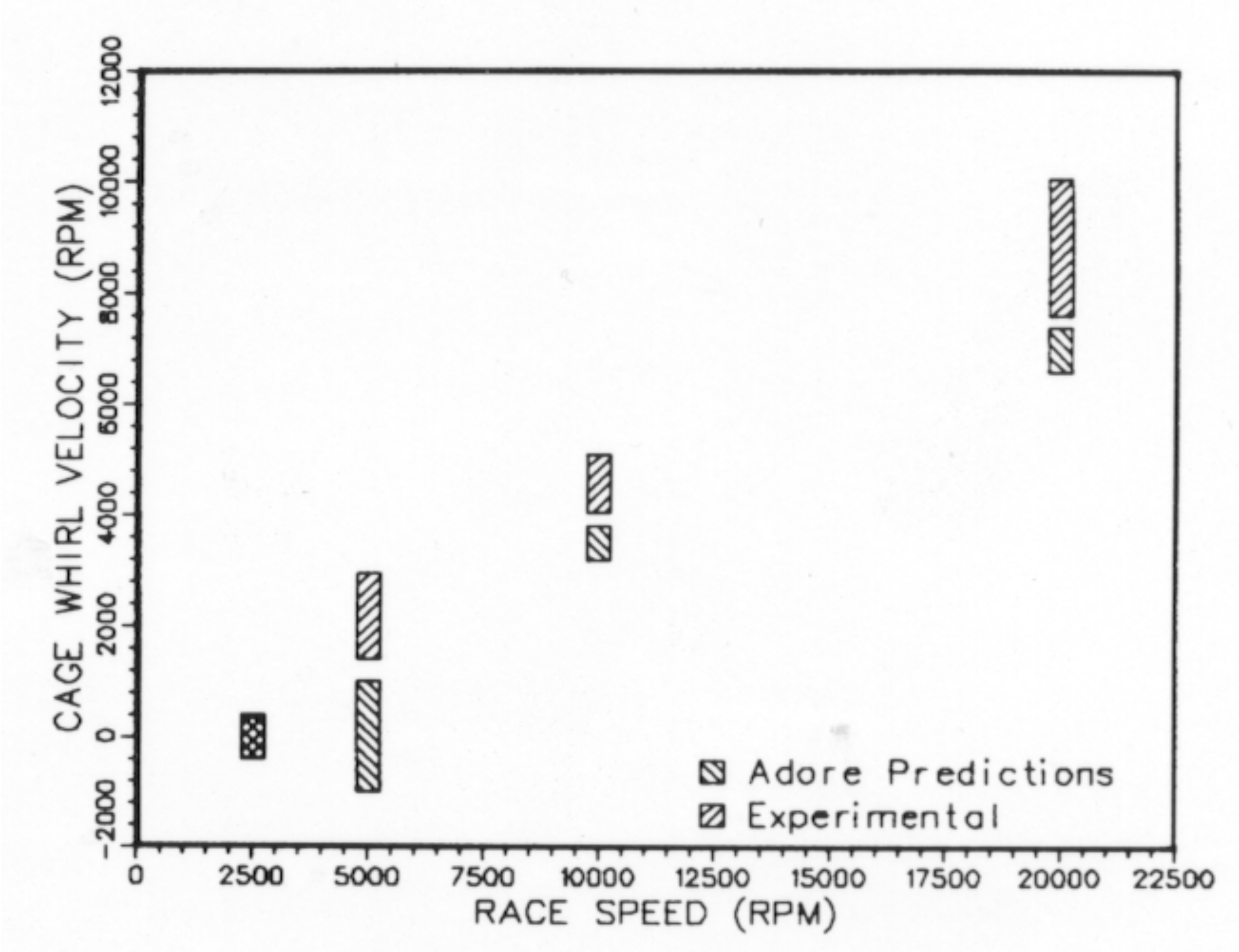
ADORE Experimental Validation
Cage Whirl Motion



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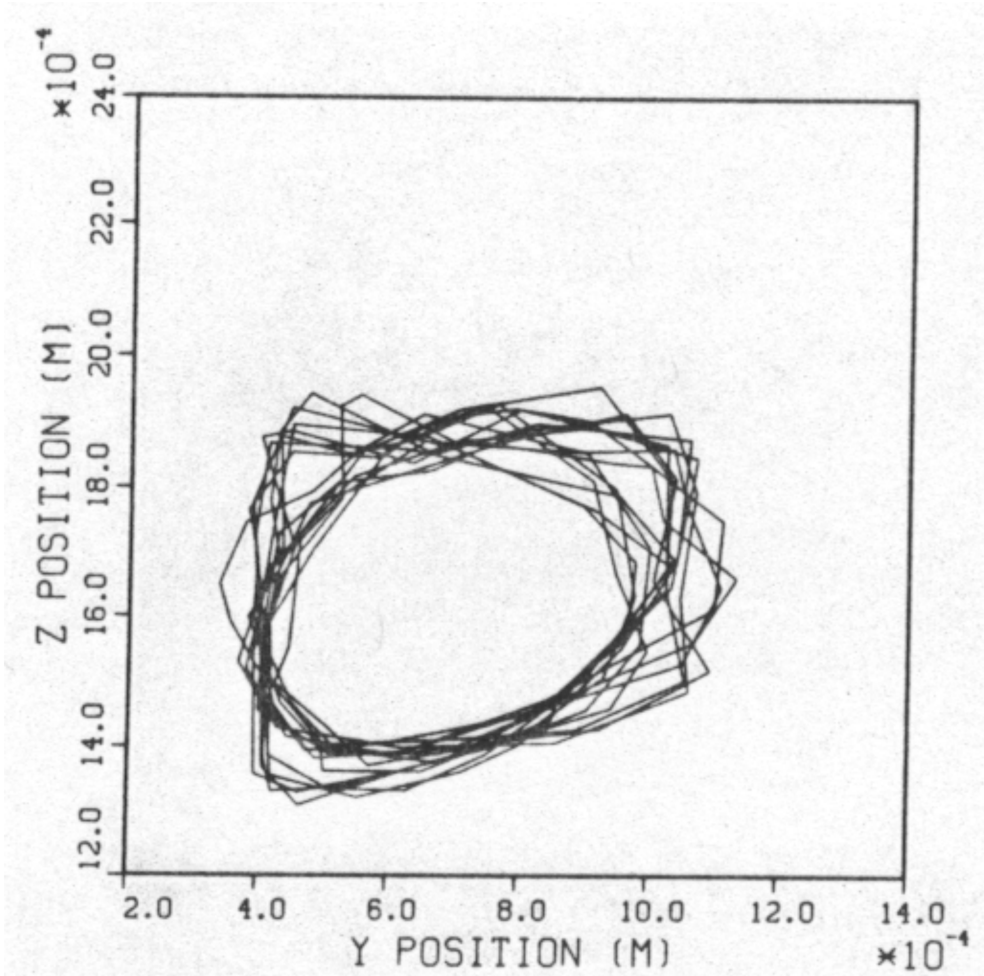
ADORE Experimental Validation
Cage Unbalance – Circular Whirl Orbits



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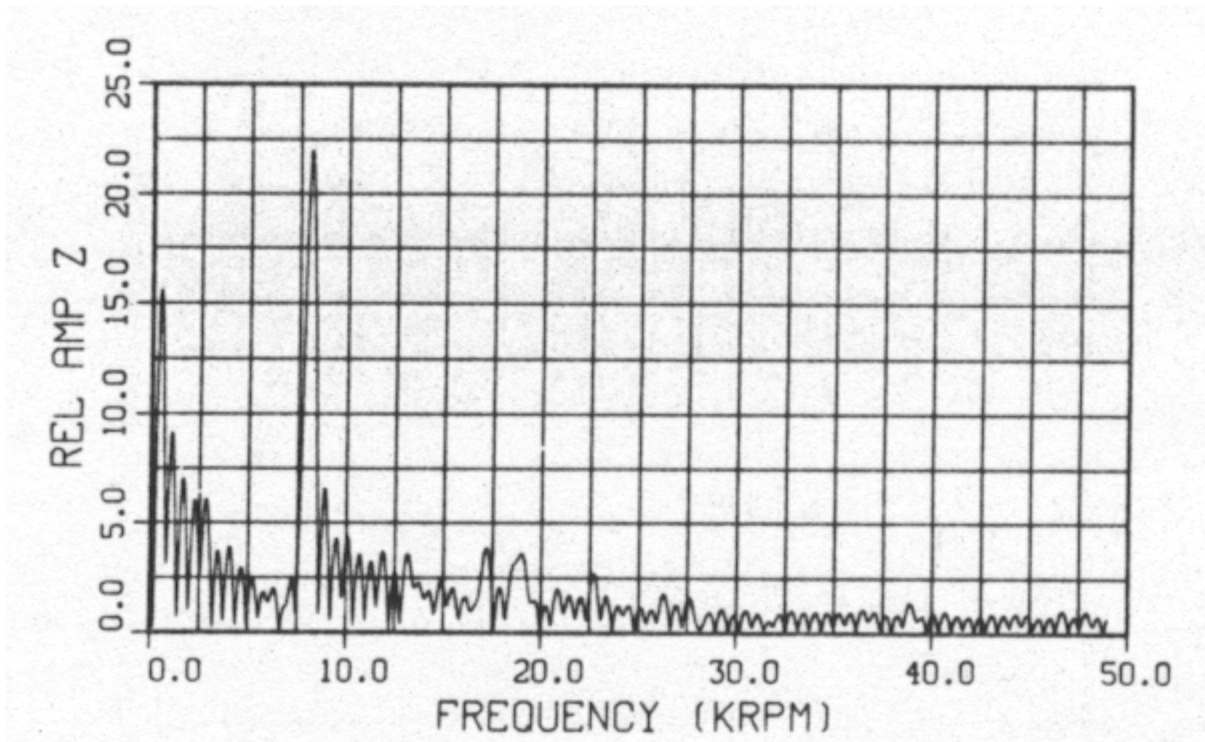
ADORE Experimental Validation
Cage Unbalance – Whirl Vel = Cage Ang Vel



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ADORE Experimental Validation
Cage Unbalance – Damage vs Unbalance

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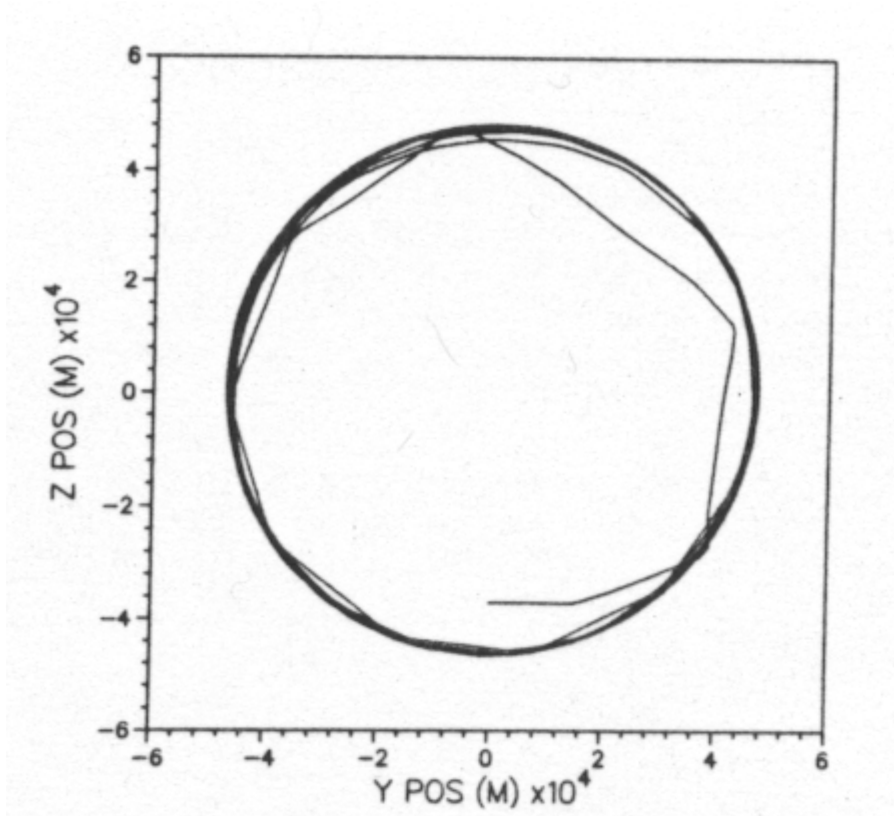
ADORE Experimental Validation
Cage Unbalance – Circular Whirl Orbits



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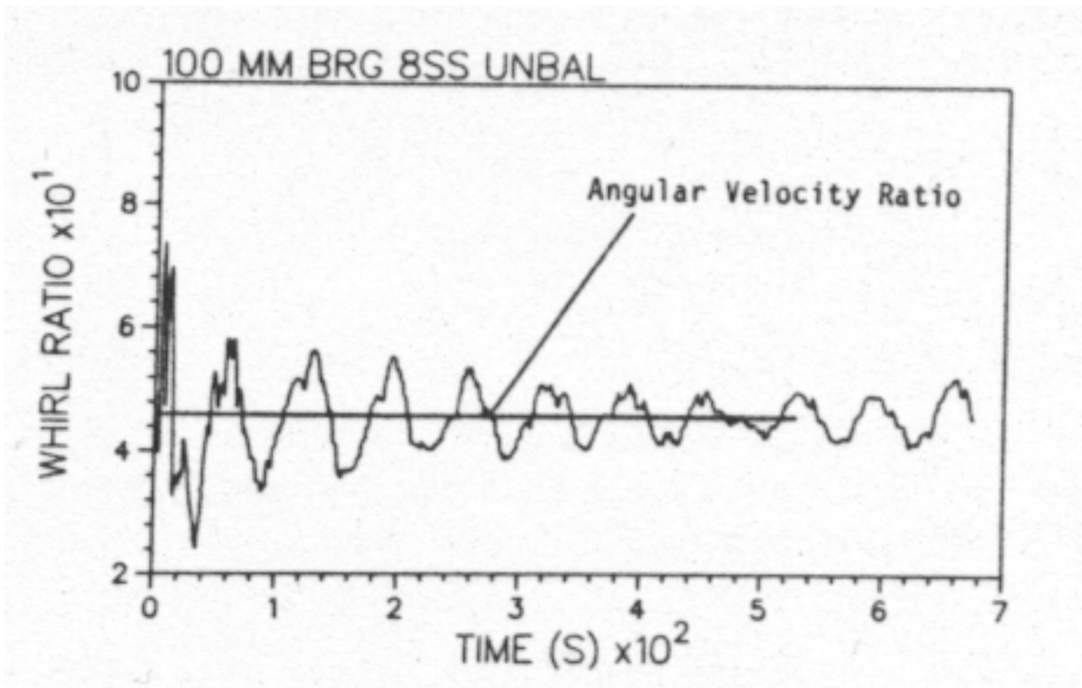

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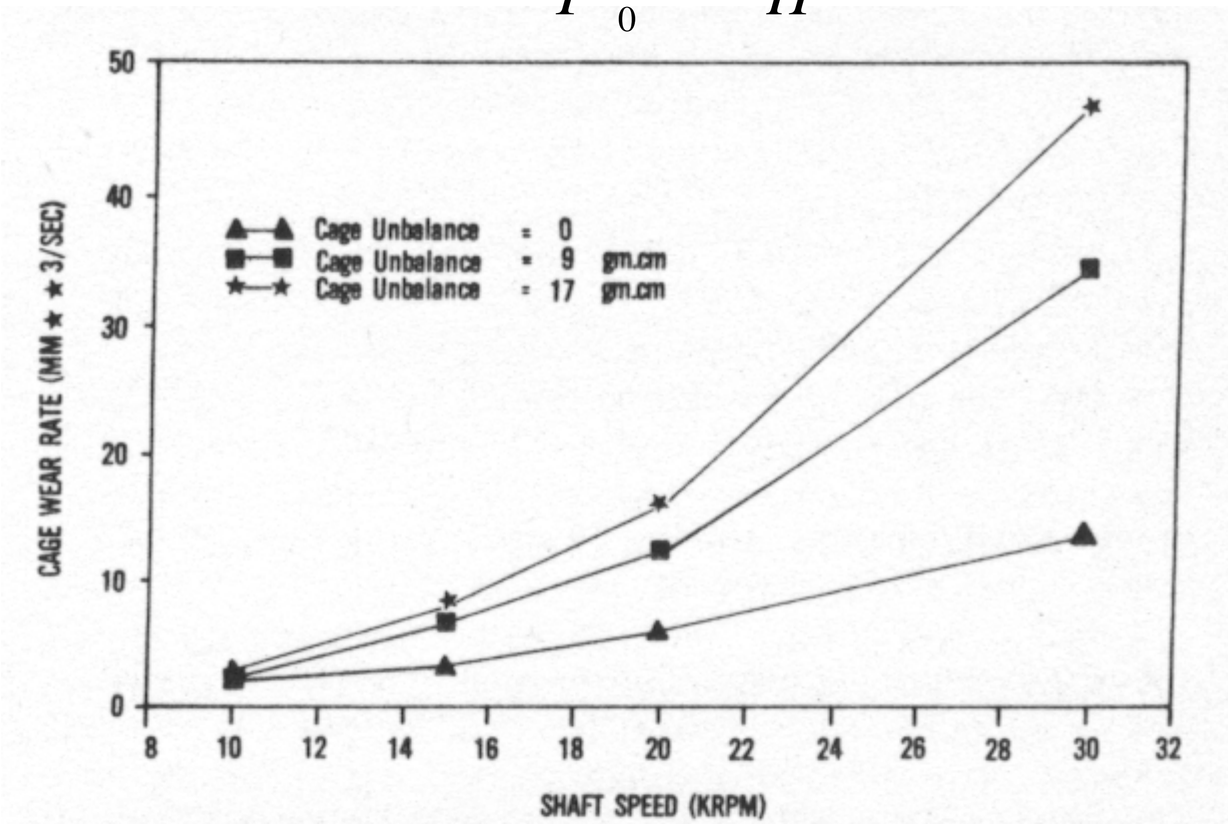
ADORE Experimental Validation
Cage Unbalance – Damage vs Unbalance

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



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Examples

- Rolling element skid
- Roller skew
- Geometrical imperfections
- Cage stability

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ADORE Examples

Significance of 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

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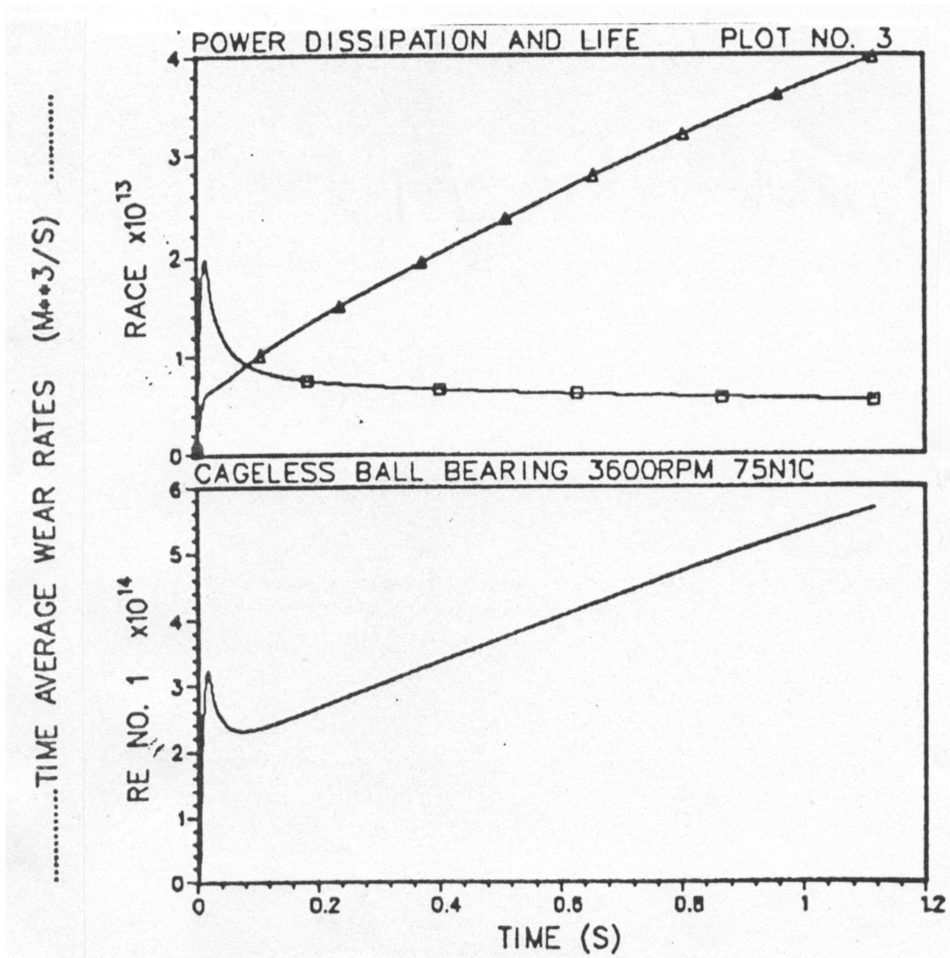
ADORE Examples

Rolling Element Skid Instability



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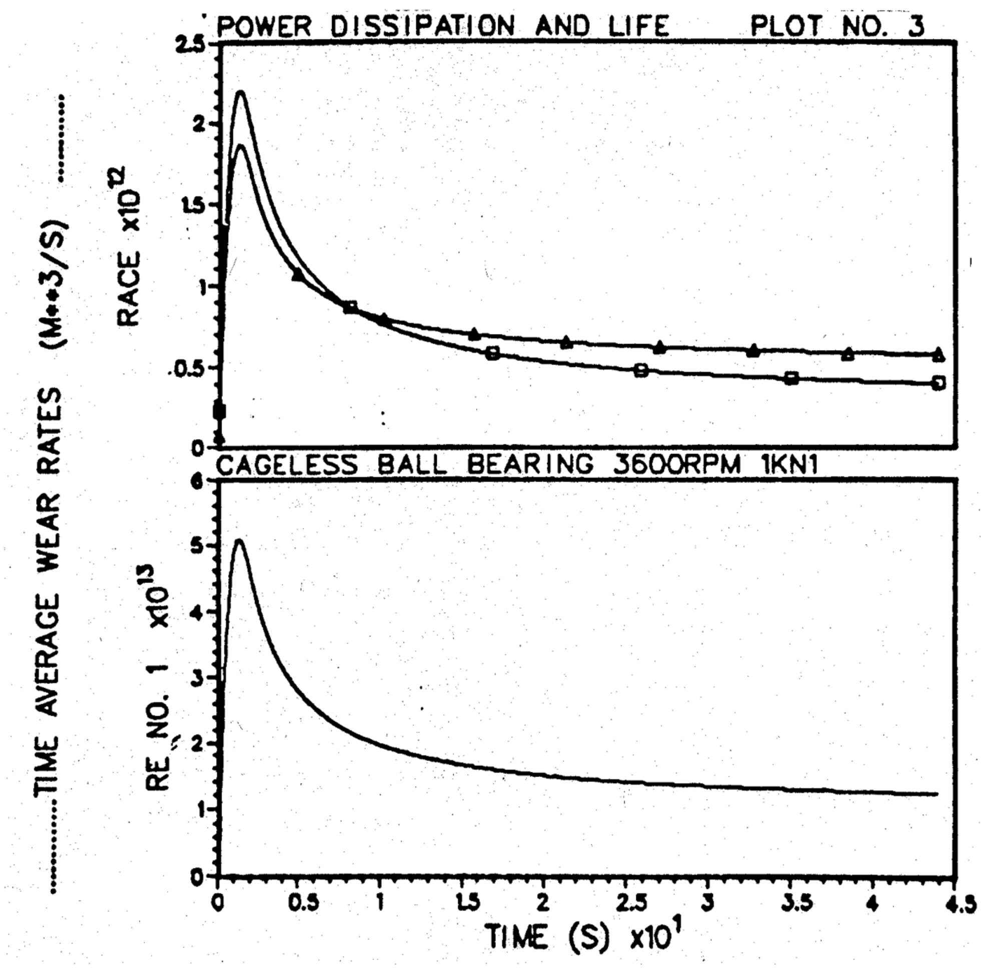
ADORE Examples

Rolling Element Skid –Stable Behavior



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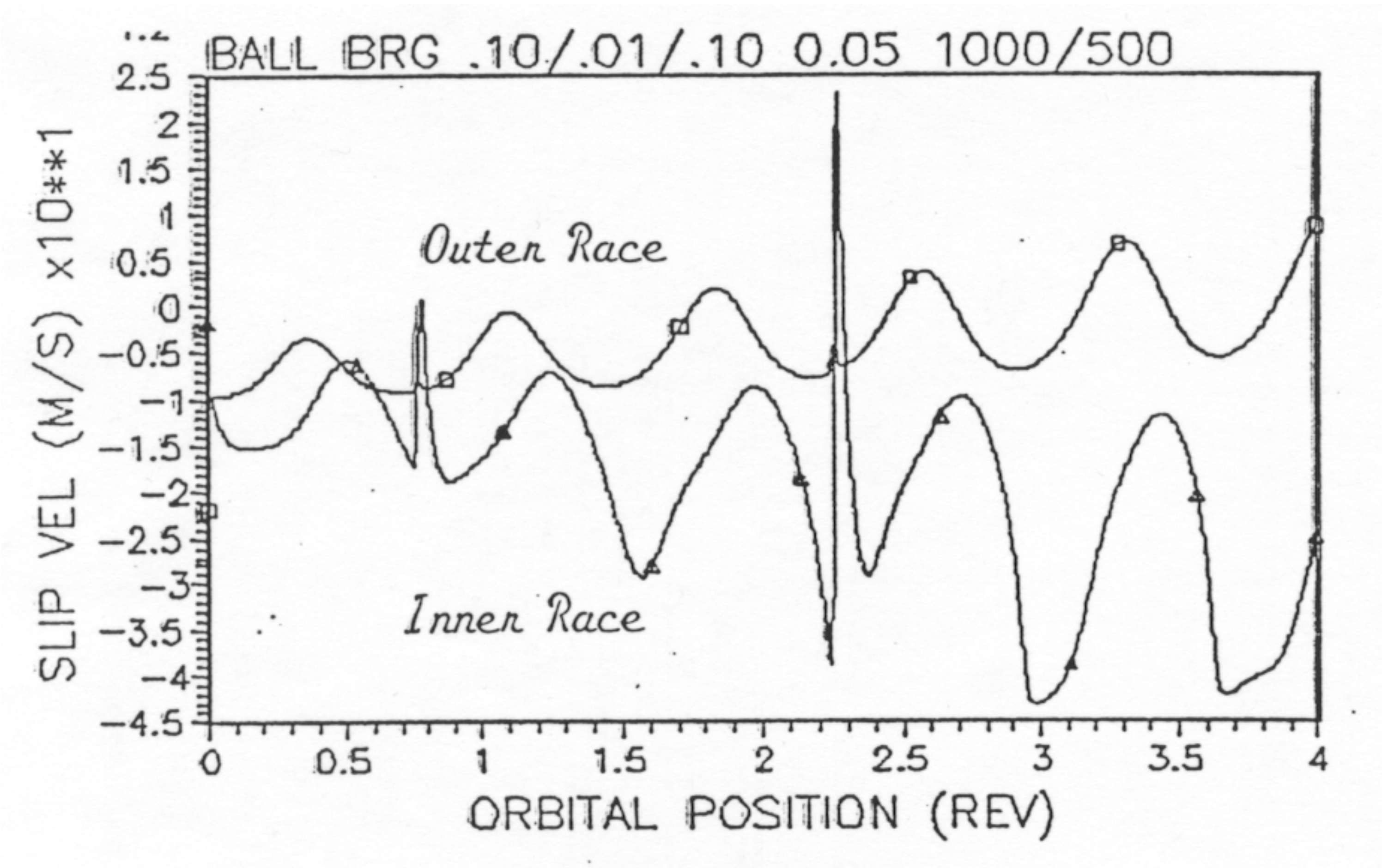
ADORE Examples

Pocket Interaction under Skid Instability



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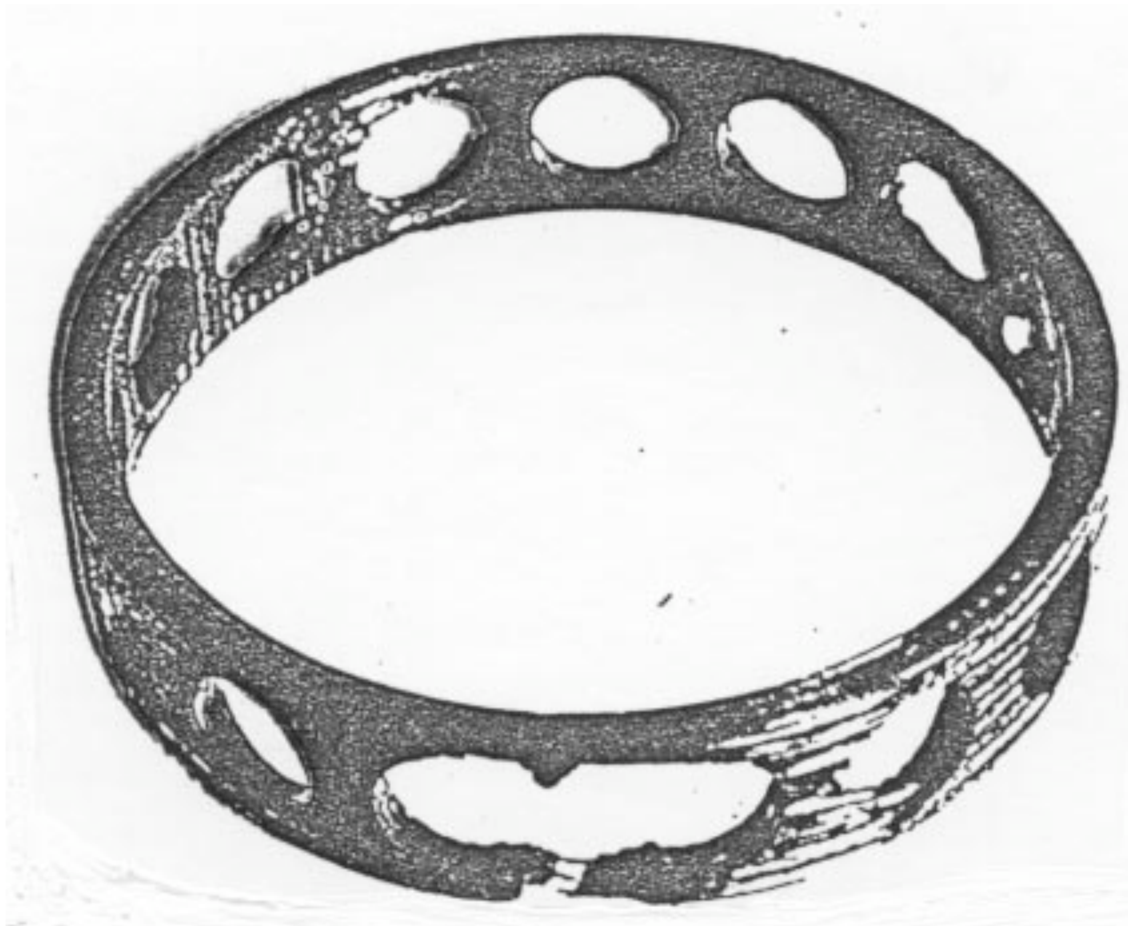
ADORE Examples

Cage Damage under Skid Instability



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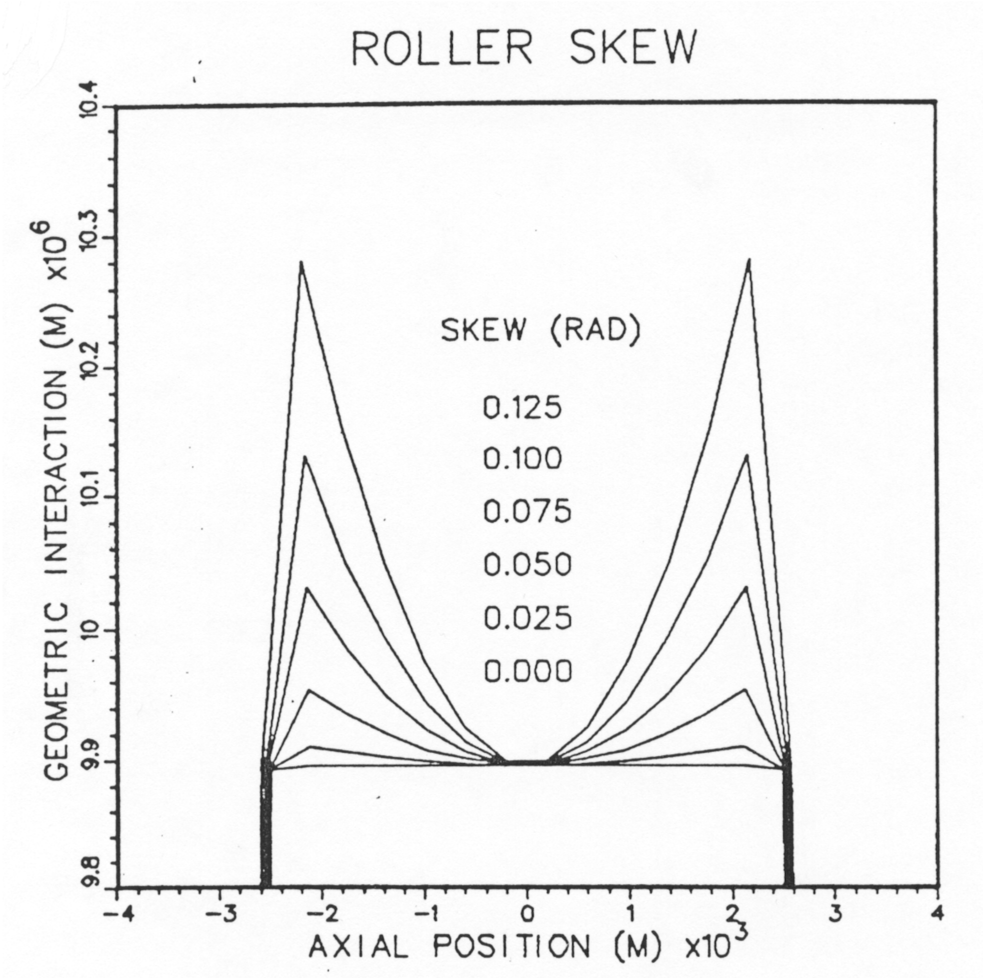
ADORE Examples

Load Distribution under Excessive Roller Skew



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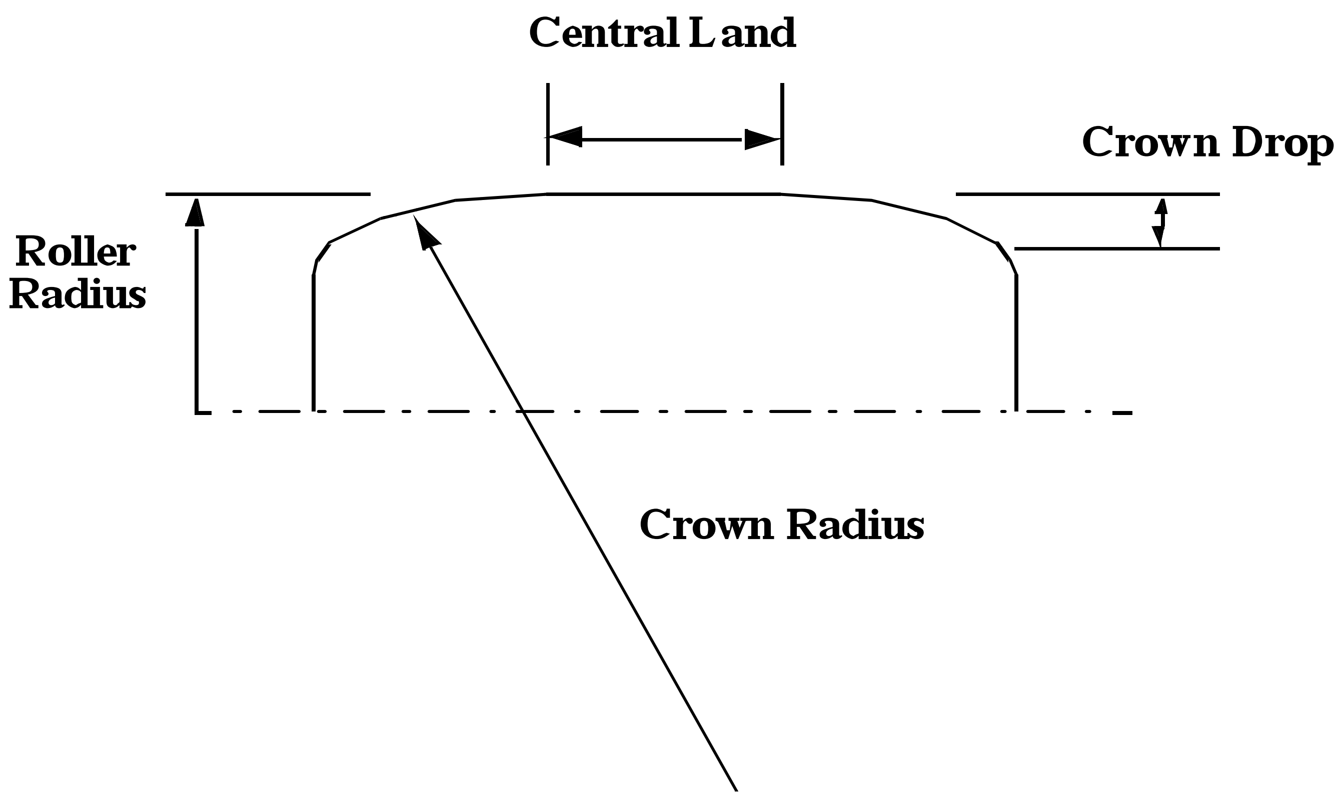
ADORE Examples

Roller Land Schematic



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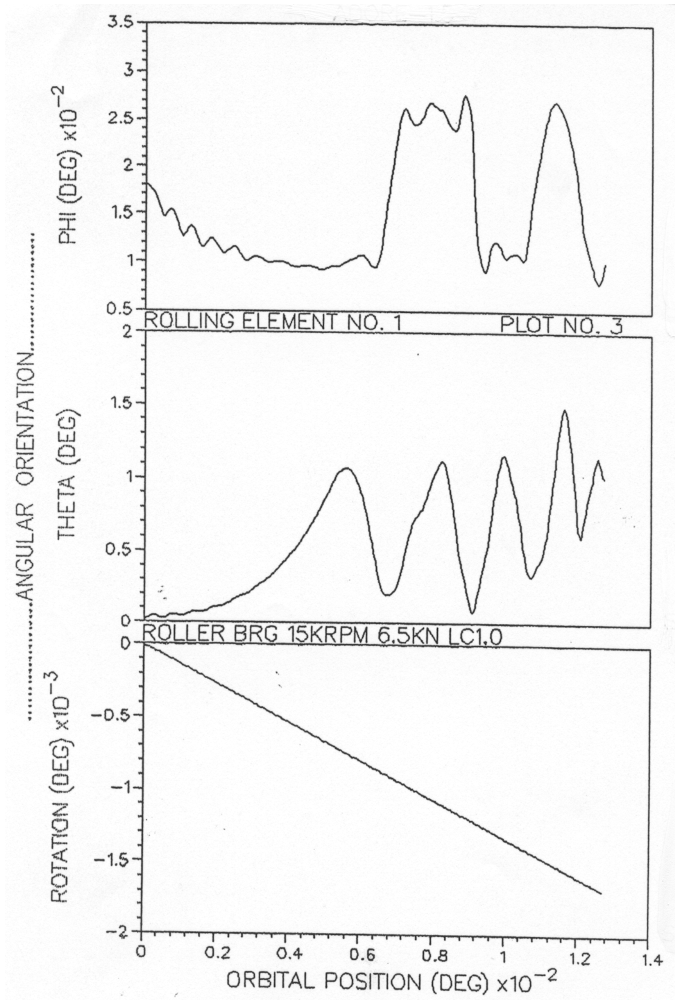
ADORE Examples

Roller Skew with Off Centered Land



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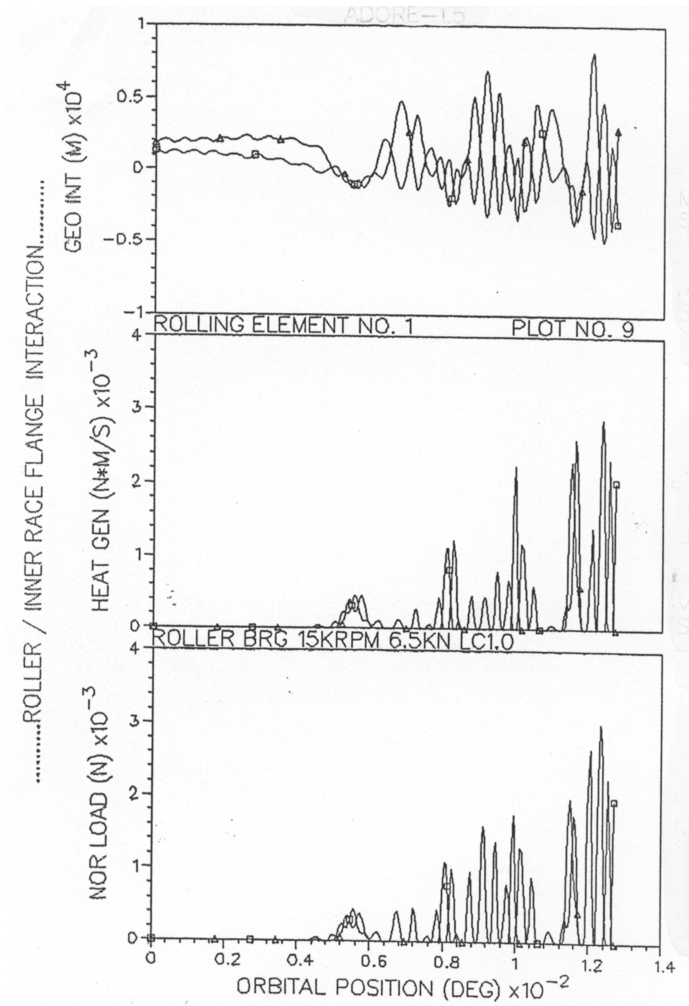
ADORE Examples

Flange Interaction with Off Centered Land



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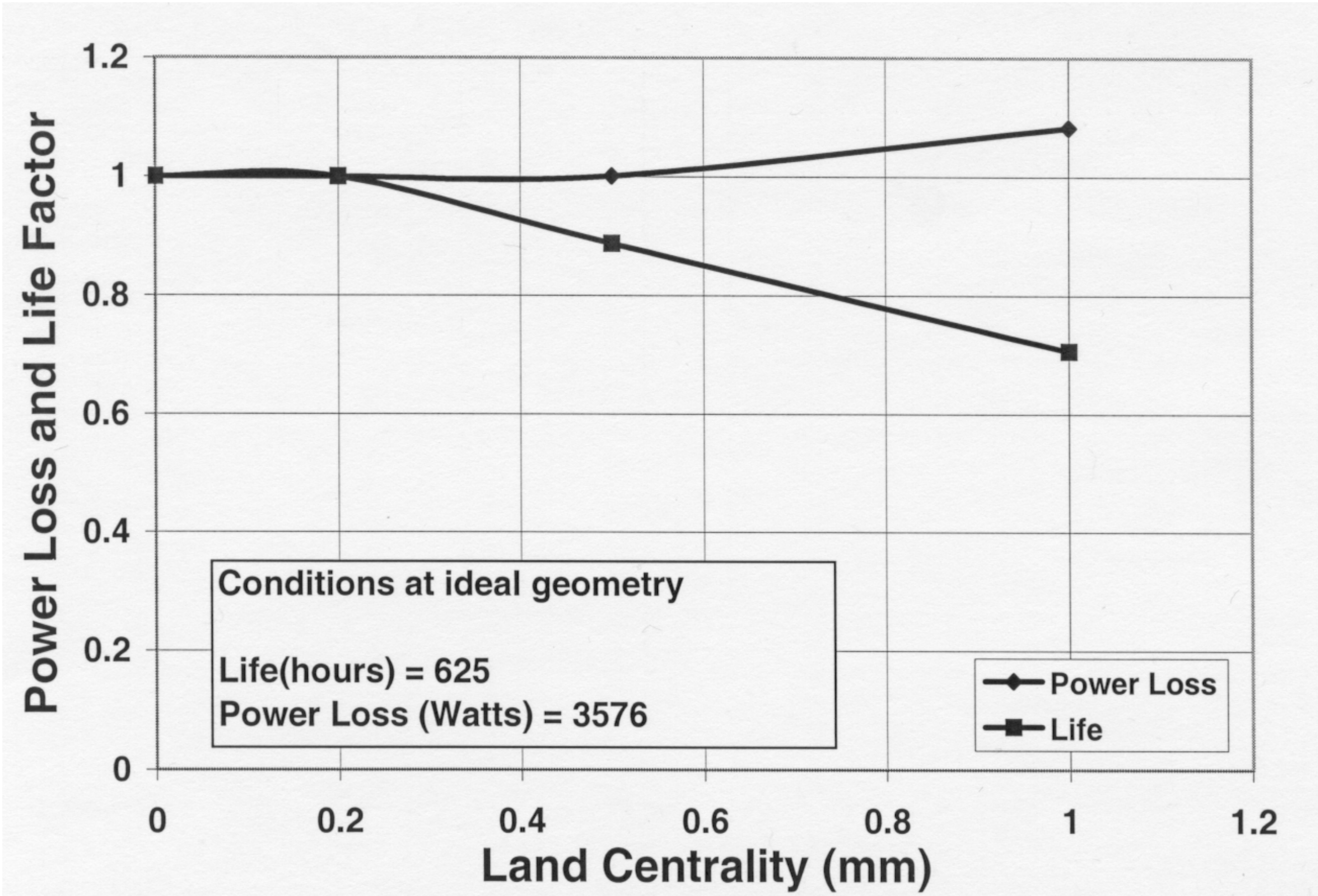
ADORE Examples

Overall Effect of Off Centered Land



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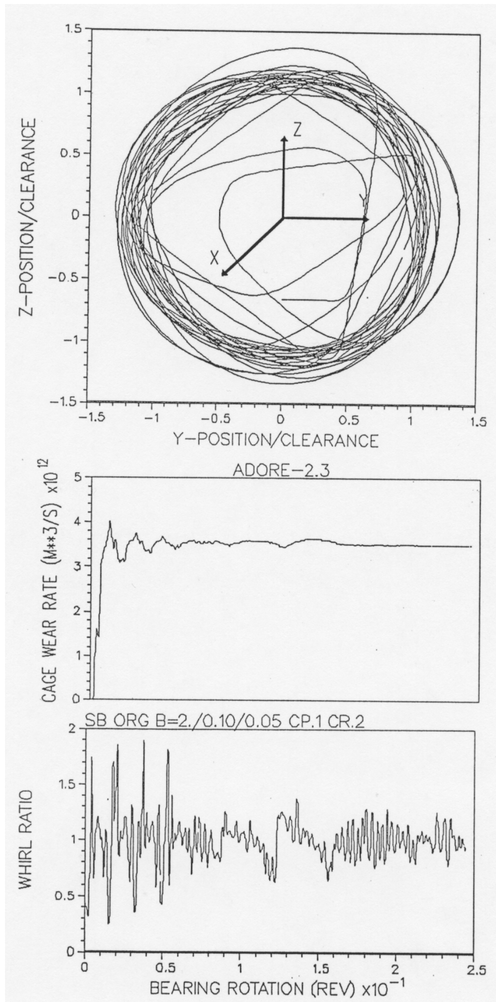
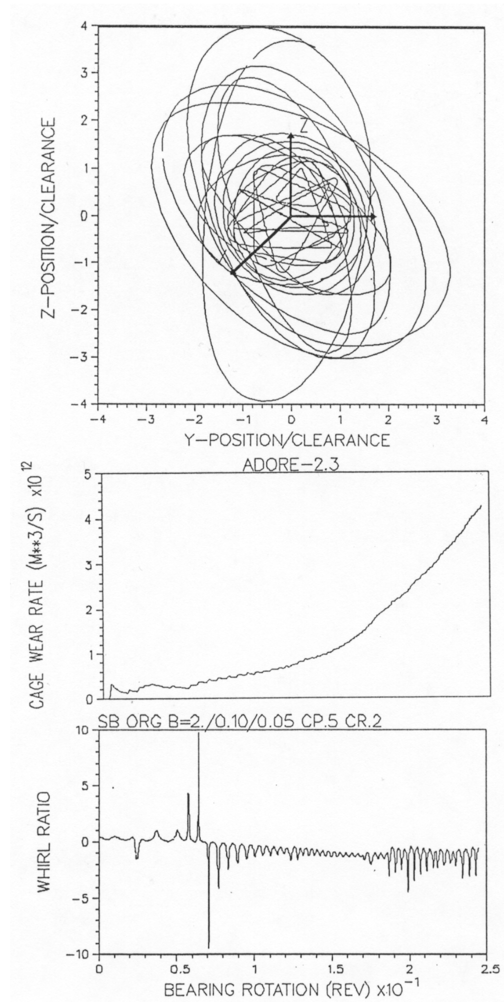
ADORE Examples

Cage Whirl Instability with Increasing Pocket Clearance





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ADORE Technical Seminar

Part 1: Program Description and Capabilities

- Introduction
- Development Fundamentals

  Break
- ADORE Overview
- Interaction Models

  Break
- Numerical Considerations
- Experimental Validation

  Break
- Examples
- **Discussion**

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- ADORE Input - Program Input and Control

  Break
- ADORE Input - Bearing Geometry
- ADORE Input - Material Properties
- ADORE Input - Operating Conditions

  Break
- ADORE Input - Frictional Interactions
- Optional Input to Graphics Module
- Data File Management

  Break
- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

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 Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- **ADORE Input - Program Input and Control**
  - Break
- ADORE Input - Bearing Geometry
- ADORE Input - Material Properties
- ADORE Input - Operating Conditions
  - Break
- ADORE Input - Frictional Interactions
- Optional Input to Graphics Module
- Data File Management
  - Break
- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

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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 Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- ADORE Input - Program Input and Control

  Break

- ADORE Input - Bearing Geometry
- ADORE Input - Material Properties
- ADORE Input - Operating Conditions

  Break

- ADORE Input - Frictional Interactions
- Optional Input to Graphics Module
- Data File Management

  Break

- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- ADORE Input - Program Input and Control

  Break

- **ADORE Input - Bearing Geometry**
- ADORE Input - Material Properties
- ADORE Input - Operating Conditions

  Break

- ADORE Input - Frictional Interactions
- Optional Input to Graphics Module
- Data File Management

  Break

- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

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ADORE Input
Bearing Geometry

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

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Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- ADORE Input - Program Input and Control

  Break

- ADORE Input - Bearing Geometry
- **ADORE Input - Material Properties**
- ADORE Input - Operating Conditions

  Break

- ADORE Input - Frictional Interactions
- Optional Input to Graphics Module
- Data File Management

  Break

- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

ADORE Input
Material Properties

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

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- ADORE Input - Program Input and Control
  - Break
- ADORE Input - Bearing Geometry
- ADORE Input - Material Properties
- **ADORE Input - Operating Conditions**
  - Break
- ADORE Input - Frictional Interactions
- Optional Input to Graphics Module
- Data File Management
  - Break
- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

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ADORE Input
Operating Conditions

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

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Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

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  - Break
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- ADORE Input - Material Properties
- ADORE Input - Operating Conditions
  - **Break**
- ADORE Input - Frictional Interactions
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  - Break
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Part 3: Program Output and User Applications

ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- ADORE Input - Program Input and Control
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- ADORE Input - Material Properties
- ADORE Input - Operating Conditions
  Break
- **ADORE Input - Frictional Interactions**
- Optional Input to Graphics Module
- Data File Management
  Break
- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

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ADORE Input
Traction Models and Frictional Interactions

- Record 10
- Model review

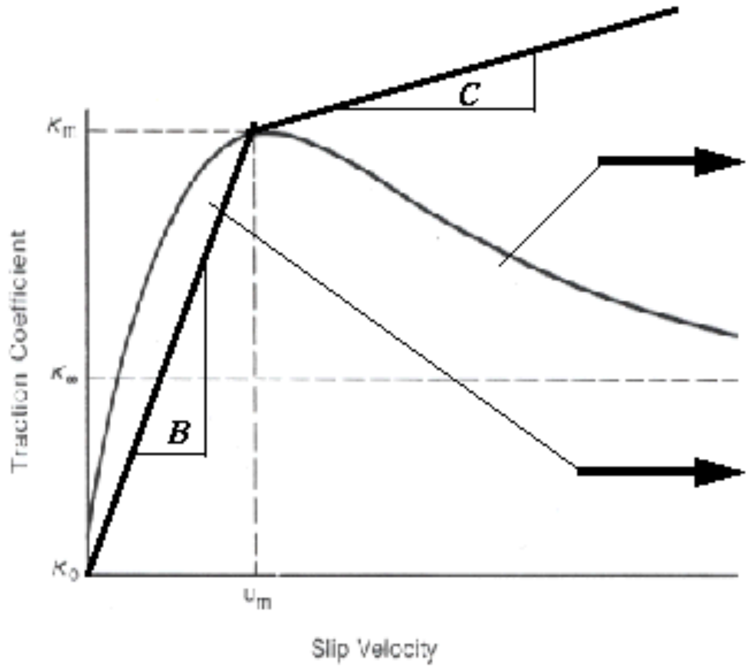
ADORE Technical Seminar

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,

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

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

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

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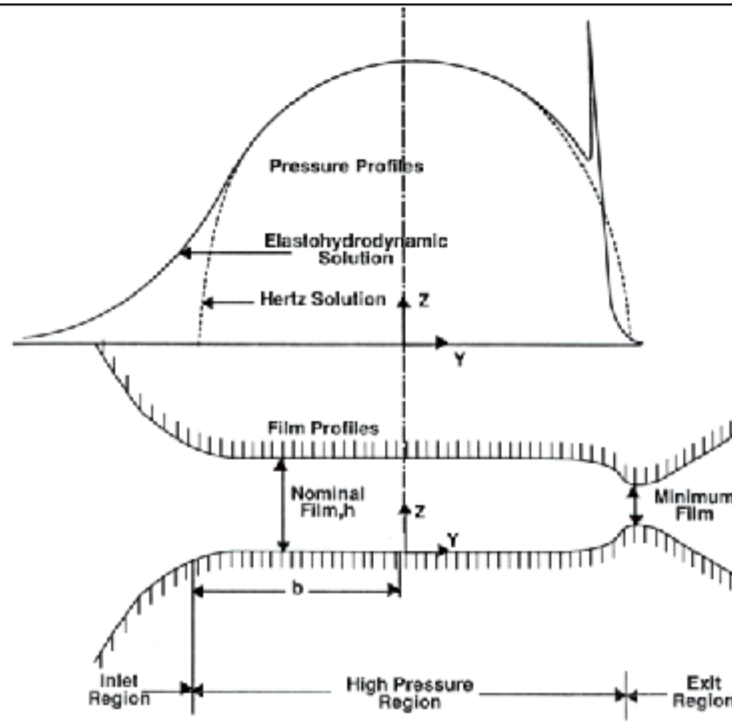
Traction Models in ADORE

Elastohydrodynamic Models



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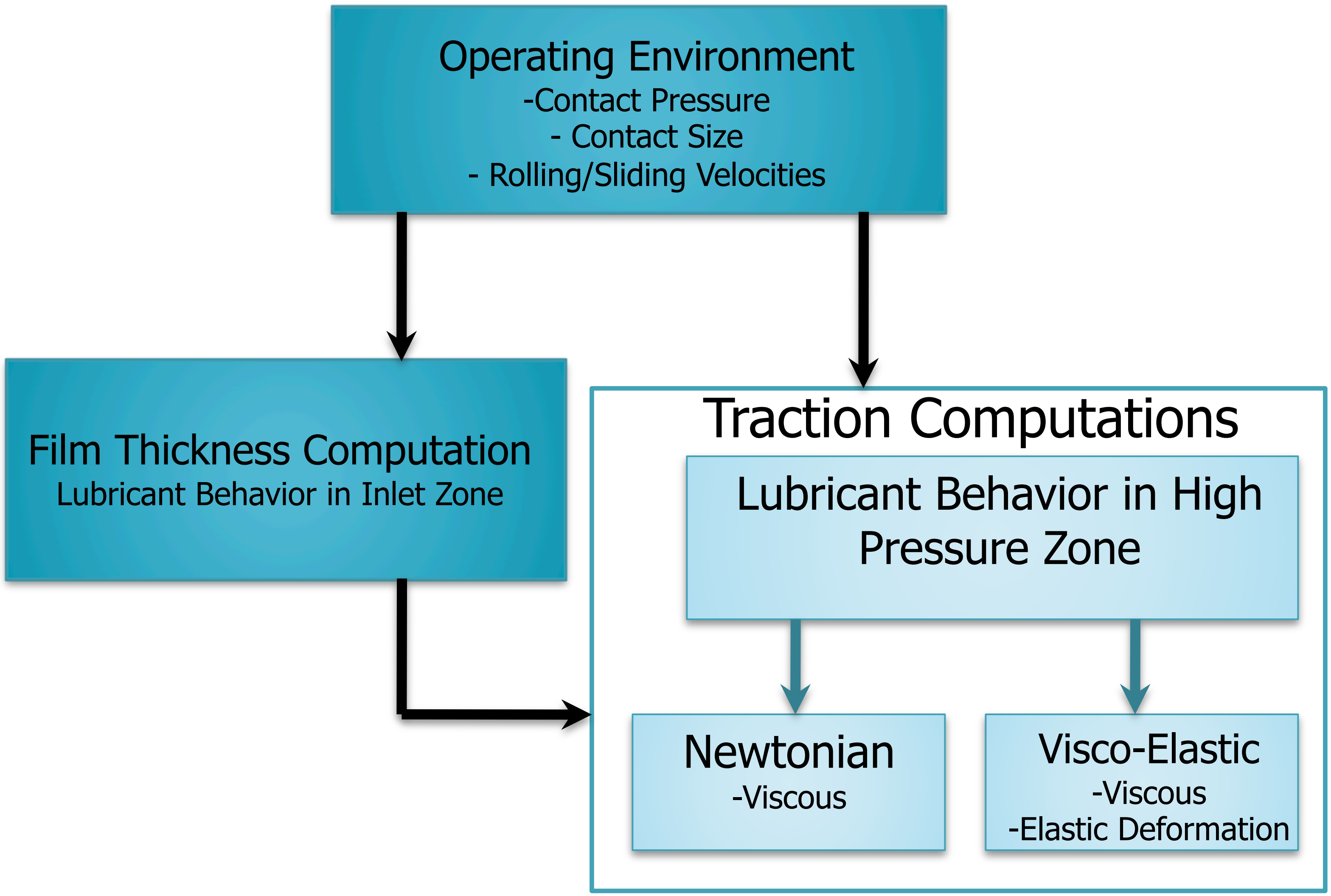
Traction Models in ADORE

Elastohydrodynamic Models – Model Schematic



Traction Models in ADORE

Elastohydrodynamic Models – Newtonian Model

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

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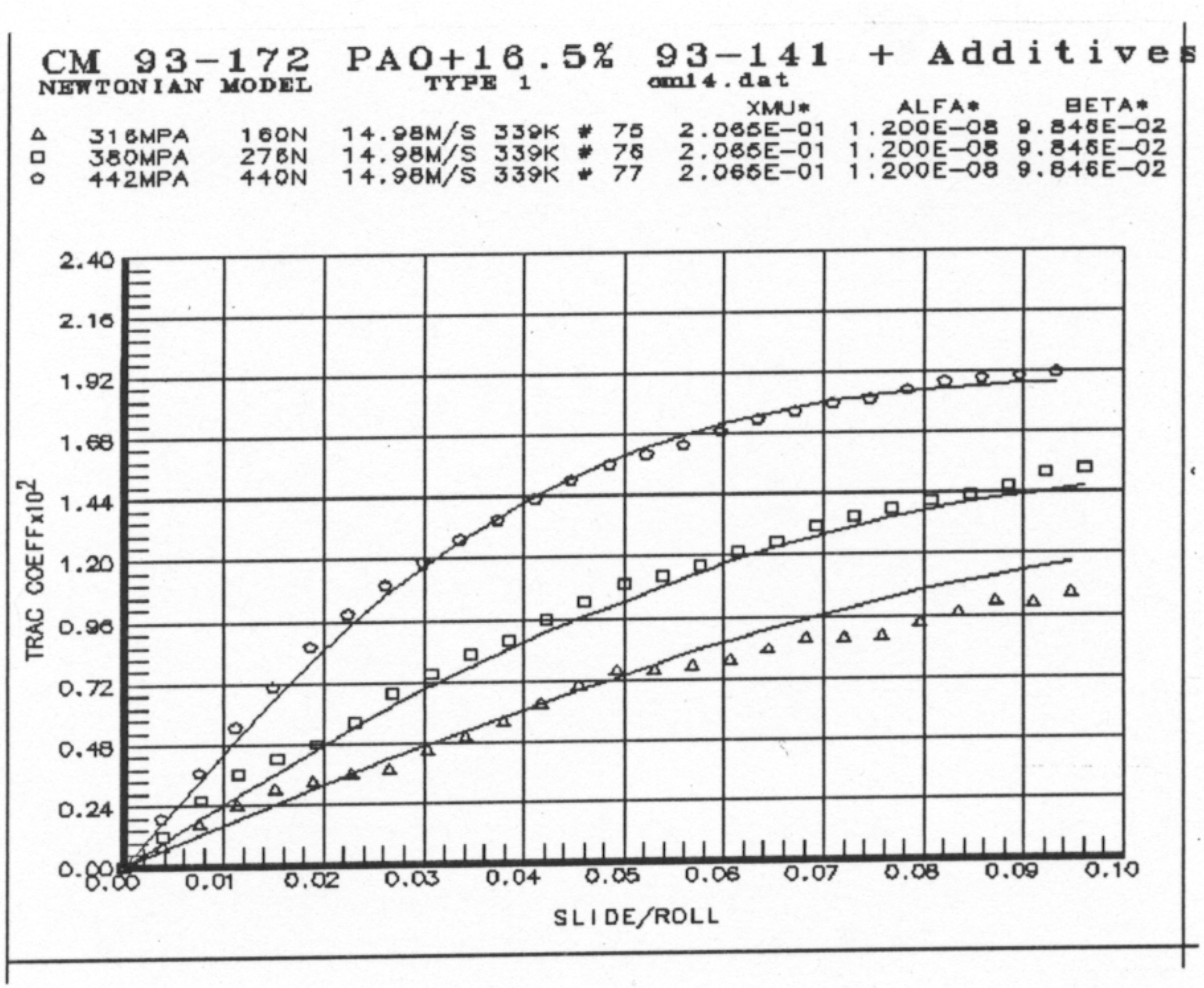
Traction Models in ADORE

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 $$f(\frac{\tau}{\tau_o}) = a\sinh(\frac{\tau}{\tau_o})$$
  - Type II $$f(\frac{\tau}{\tau_o}) = a\tanh(\frac{\tau}{\tau_o})$$

- Viscosity relations
  - 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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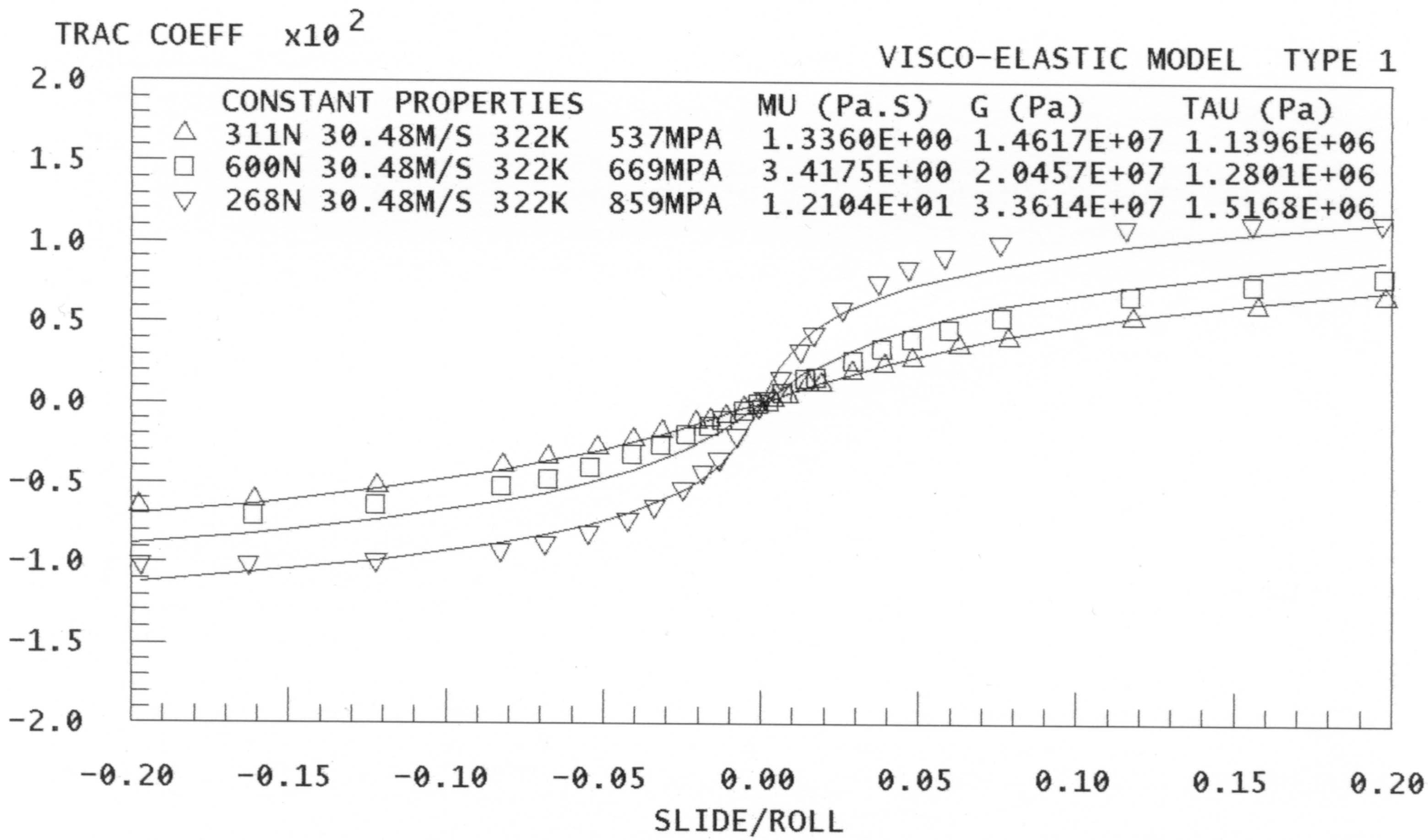
Traction Models in ADORE

Visco-Elastic Model Validation



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ADORE Input
Frictional Interactions & Gravity Effects

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

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ADORE Input

Inputs for User Programmable Subroutines

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

ADORE Input

Optional Inputs to Graphics Facilities

- Range of Data
- Data file selection
- Desired plots or animated views
- All inputs are interactive

ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

- ◆ADORE Input - Program Input and Control
  Break
- ◆ADORE Input - Bearing Geometry
- ◆ADORE Input - Material Properties
- ◆ADORE Input - Operating Conditions
  Break
- ◆ADORE Input - Frictional Interactions
- ◆Optional Input to Graphics Module
- ◆**Data File Management**
  Break
- ◆User Programmable Routines
- ◆Discussion

Part 3: Program Output and User Applications

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
Data Format

- All files are readable text files
- Typical views
  - DATA.txt file
  - PRINT.txt file
  - Typical SOL file

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  Break

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  Break

- User Programmable Routines
- Discussion

Part 3: Program Output and User Applications

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ADORE User Programmable Procedures

Routines 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 of Optional Subroutine

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

ADORE User Programmable Procedures
Model Development & ADORE Interface

- Test area in ADORE
- ADORE source code view

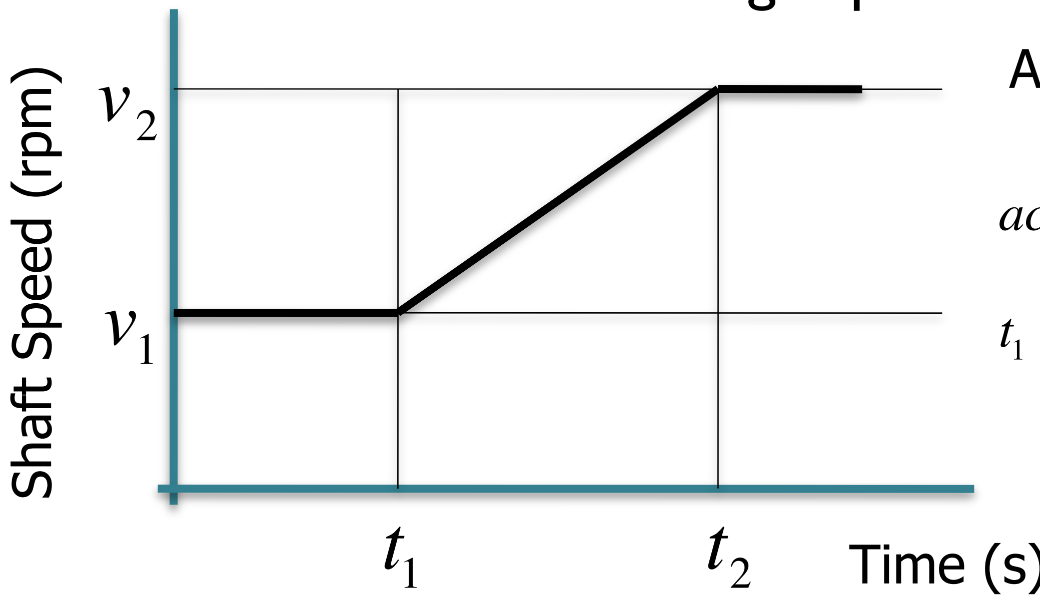
```
…
…
…
      call Adra1                                                            ! input data
      if (ierInd /= 0) call Adra9                                           ! process error if any, ierInd->Errors
      call Adra2                                                            ! initial computations and set up
!-------------------------------------
!   test area
!-----------

         Insert optional routine calls and debugging information here

!-------------------------------------
      call InitialConditions                                                ! set up initial conditions
!--------------------------------------
!     index of rotating race for output
…
…
…
```

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

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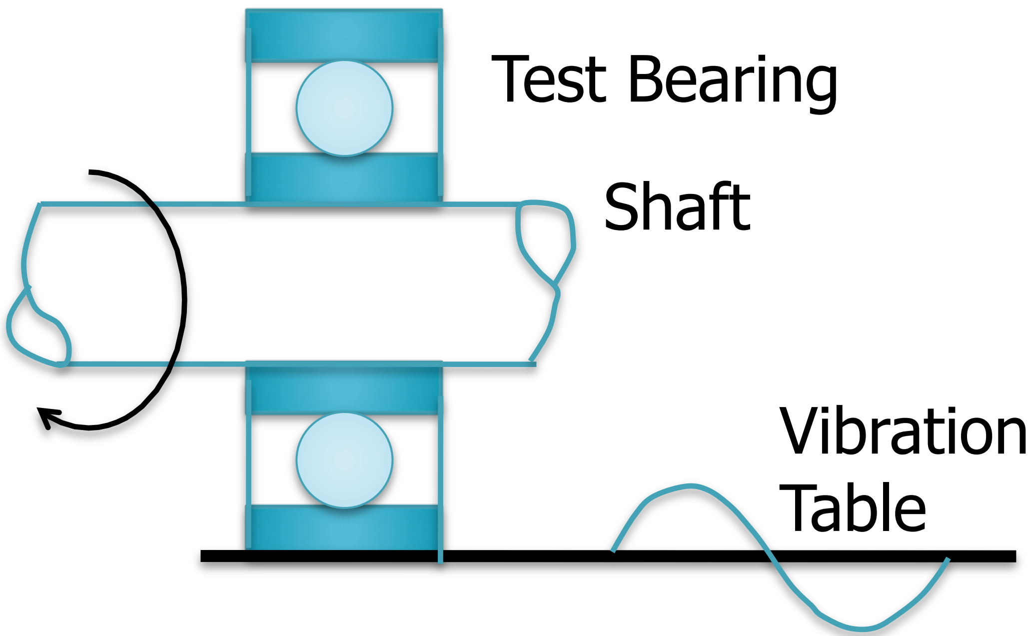
ADORE User Programmable Procedures
Example 2: Vibrational Loading

- 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

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Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

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  Break
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- ◆ADORE Input - Material Properties
- ◆ADORE Input - Operating Conditions
  Break
- ◆ADORE Input - Frictional Interactions
- ◆Optional Input to Graphics Module
- ◆Data File Management
  Break
- ◆User Programmable Routines
- ◆**Discussion**

Part 3: Program Output and User Applications

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

- **ADORE Print Output**
- ADORE Plot Output
- Graphics Animation - AGORE

  Break
- Critical Performance Parameters
- Computing effort optimization
- Summary
- Discussion

  Break
- User Applications and General Discussion

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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

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Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

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- ADORE Print Output
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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 Plot Output

Plot Facility AdrPlot

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

ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

- ADORE Print Output
- ADORE Plot Output
- **Graphics Animation - AGORE**

  Break
- Critical Performance Parameters
- Computing effort optimization
- Summary
- Discussion

  Break
- User Applications and General Discussion

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Graphic Animation AGORE
Animated Graphics Of Rolling Elements

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

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 Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

Break

- Critical Performance Parameters
- Computing effort optimization
- Summary
- Discussion

Break

- User Applications and General Discussion

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

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Part 3: Program Output and User Applications

- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

  Break

- **Critical Performance Parameters**
- Computing effort optimization
- Summary
- Discussion

  Break

- User Applications and General Discussion

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Critical Performance Parameters
Design Optimization Procedures

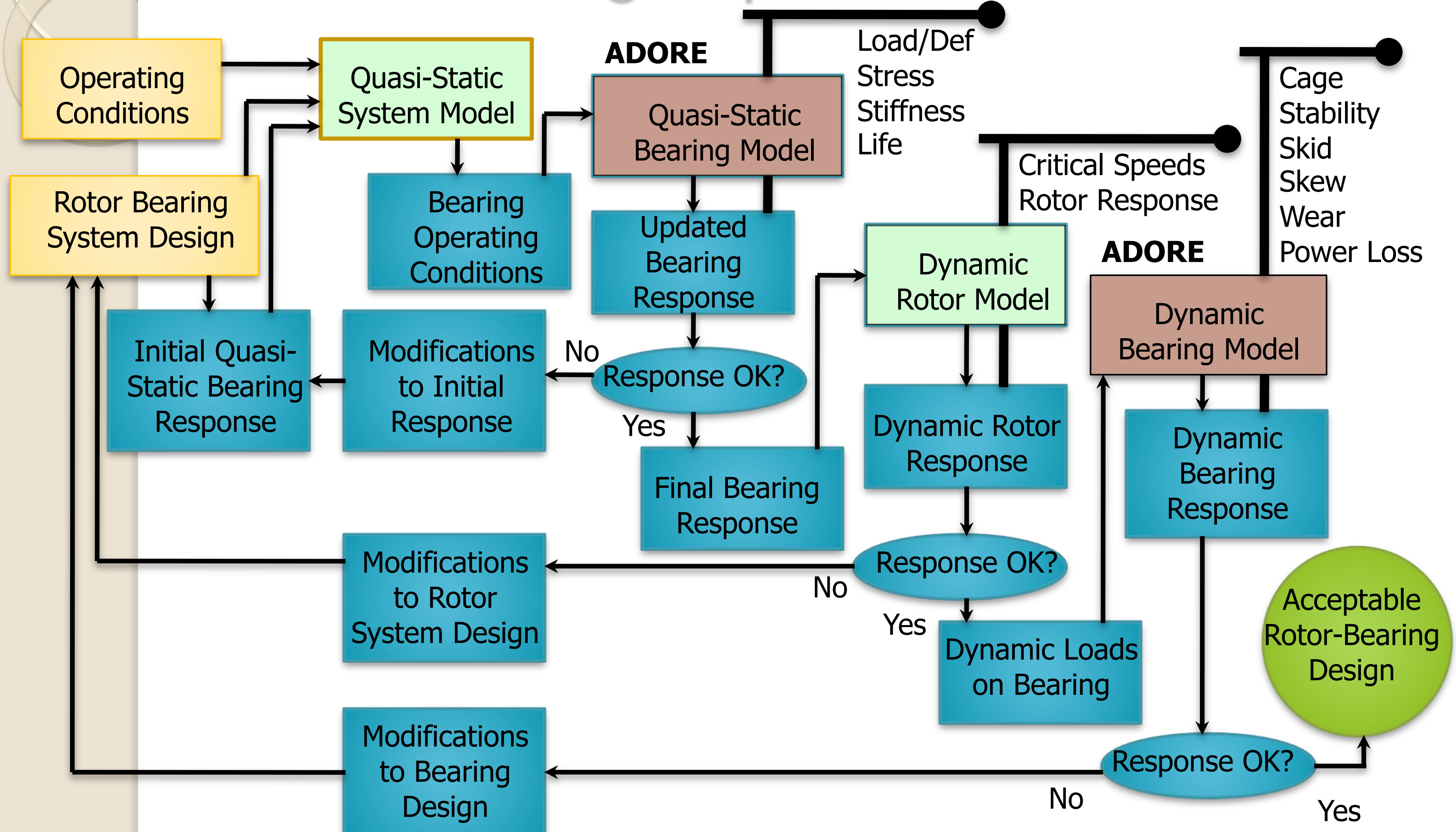
- Bearing life
- Power loss
- Wear
- Stability
- Dynamic variations

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



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Practical Design Development

Significant Parameters in Dynamics Modeling

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

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Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

  Break

- Critical Performance Parameters
- **Computing effort optimization**
- Summary
- Discussion

  Break

- User Applications and General Discussion

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Computing Effort Optimization

- Rapidly advancing computing speed
  - Required computing effort may not be a problem
- Progressively increasing design sophistications
  - Warrant more advanced modeling techniques
  - More sophisticated dynamic interactions
- Advancing computing horse power is continually facilitating model advancement
- Understanding of computing requirement is essential for increasingly sophisticated modeling

Computing Effort Optimization
Basic Elements in ADORE

- Computing time per time step
- Size of time step

Subject	Computing Time per Time Step	Time Step Size
Equilibrium constraint	Increases	Increases
Order of integrating method	Increases	Increases
Increasing truncation limit	Insensitive	Increases
Model complexity	Increases	Uncertain

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

  Break
- Critical Performance Parameters
- Computing effort optimization
- **Summary**
- Discussion

  Break
- User Applications and General Discussion

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ADORE Technical Seminar

Summary

- ✓ Review of rolling bearing computer models
- ✓ Salient features of ADORE
- ✓ Experimental validation
- ✓ Examples
- ✓ Input/Output description
- ✓ Design Optimization
- ✓ Computational considerations

ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

  Break
- Critical Performance Parameters
- Computing effort optimization
- Summary
- **Discussion**

  Break
- User Applications and General Discussion

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

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- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

  Break

- Critical Performance Parameters
- Computing effort optimization
- Summary
- Discussion

  Break

- User Applications and General Discussion

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ADORE Technical Seminar

Part 1: Program Description and Capabilities

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- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

  Break

- Critical Performance Parameters
- Computing effort optimization
- Summary
- Discussion

  Break

- **User Applications and General Discussion**

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ADORE Execution Problems

- Input data review
- Truncation error diagnostic
- Minimum step size
- Rolling element/Race traction behavior

ADORE Execution Problems

Input Data Review

- Execute a zero step run
- Examine all input data thoroughly
- Make any corrections if necessary

ADORE Execution Problems

Diagnostic Message from ADORE

- System generated runtime error
  - Errors could not be arrested in ADORE
  - Termination due to fatal error
  - Zero-divide, Negative argument of SQRT, or similar
  - Array bounds
  - Other runtime problems
- ADORE Diagnostics
  - Problem recognized by ADORE
  - Appropriate diagnostic is printed to assist resolution
  - Overall ADORE development objectives
- Arrest as many errors as possible

ADORE Execution Problems
Truncation Error Diagnostic

- Frequent diagnostic

```
Encountered error code:  101     Supplementary code:    0

    Truncation limit encountered

    Step, subStep numbers and Equation ID are:
       290      0   119
```

ADORE Execution Problems

Equation ID

- Differential equation resulting in maximum truncation error

$$Equation\# = Mod((equationID - 1), 12)$$

$$Equation\# = Mod((119 - 1), 12) = 10$$

- This bearing has 18 balls
- Equation #10 for element #10
- Angular Acceleration for element #10
- Suspect – Lubricant traction

ADORE Execution Problems

Equation ID – Examine Ball/Race Slip and Traction

- Ball/Race rolling velocity

	RE	..Rolling Velocity.. (m/s) Outer Race	Inner Race	Centrifugal Force (N)
	1	1.279E+02	1.260E+02	5.138E+03
	2	1.279E+02	1.260E+02	5.136E+03
	3	1.279E+02	1.260E+02	5.133E+03
	4	1.279E+02	1.260E+02	5.129E+03
	5	1.279E+02	1.260E+02	5.126E+03
	6	1.279E+02	1.260E+02	5.127E+03
	7	1.279E+02	1.261E+02	5.125E+03
	8	1.278E+02	1.261E+02	5.124E+03
	9	1.279E+02	1.261E+02	5.125E+03
>>>	10	1.276E+02	1.259E+02	5.115E+03
	11	1.277E+02	1.262E+02	5.112E+03
	12	1.277E+02	1.262E+02	5.115E+03
	13	1.277E+02	1.262E+02	5.111E+03
	14	1.276E+02	1.262E+02	5.107E+03
	15	1.276E+02	1.262E+02	5.106E+03
	16	1.276E+02	1.262E+02	5.103E+03
	17	1.277E+02	1.261E+02	5.125E+03
	18	1.278E+02	1.260E+02	5.140E+03

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ADORE Execution Problems

Equation ID – Examine Ball/Race Slip and Traction

- Corresponding Traction/Slip

RE no	Max Slip Velocity (m/s)		Trac Coeff		Lubricant Film (m)		Max Stress*Slip (Pa.m/s)		Normalized Position of Max Stress*Slip		Relative Orb Pos (rad)
	Outer Race	Inner Race	Outer Race	Inner Race	Outer Race	Inner Race	Outer Race	Inner Race	Outer Race	Inner Race	
1	1.036E+01	1.001E+01	1.600E-02	9.505E-02	1.147E-07	1.287E-07	1.067E+10	1.158E+10	-6.779E-01	6.456E-01	3.832E-03
2	1.019E+01	1.009E+01	1.600E-02	9.355E-02	1.150E-07	1.303E-07	1.046E+10	1.166E+10	-6.857E-01	6.440E-01	2.607E-03
3	1.006E+01	1.013E+01	1.600E-02	9.144E-02	1.160E-07	1.330E-07	1.028E+10	1.167E+10	-6.930E-01	6.421E-01	1.140E-03
4	9.984E+00	1.012E+01	1.600E-02	8.909E-02	1.175E-07	1.366E-07	1.017E+10	1.162E+10	-6.990E-01	6.400E-01	-4.438E-04
5	9.985E+00	1.007E+01	1.600E-02	8.681E-02	1.194E-07	1.407E-07	1.015E+10	1.149E+10	-7.020E-01	6.387E-01	-1.658E-03
6	1.009E+01	9.962E+00	1.600E-02	8.485E-02	1.213E-07	1.450E-07	1.026E+10	1.127E+10	-6.995E-01	6.392E-01	-2.730E-03
7	1.026E+01	9.834E+00	1.600E-02	8.344E-02	1.232E-07	1.485E-07	1.045E+10	1.105E+10	-6.962E-01	6.392E-01	-4.050E-03
8	1.035E+01	9.756E+00	1.600E-02	8.239E-02	1.245E-07	1.512E-07	1.056E+10	1.091E+10	-6.943E-01	6.391E-01	-2.024E-03
9	1.032E+01	9.763E+00	1.600E-02	8.165E-02	1.250E-07	1.525E-07	1.052E+10	1.090E+10	-6.948E-01	6.388E-01	1.348E-03
>>> 10	1.048E+01	1.015E+01	9.407E-02	8.052E-02	1.273E-07	1.509E-07	1.072E+10	1.152E+10	-6.764E-01	6.135E-01	-1.281E-04
11	1.042E+01	9.745E+00	1.600E-02	8.305E-02	1.248E-07	1.499E-07	1.064E+10	1.093E+10	-6.979E-01	6.345E-01	-2.247E-03
12	1.054E+01	9.713E+00	1.600E-02	8.473E-02	1.238E-07	1.472E-07	1.081E+10	1.093E+10	-6.923E-01	6.362E-01	-1.091E-03
13	1.059E+01	9.732E+00	1.600E-02	8.696E-02	1.224E-07	1.431E-07	1.089E+10	1.103E+10	-6.922E-01	6.351E-01	-9.394E-04
14	1.060E+01	9.776E+00	1.600E-02	8.946E-02	1.208E-07	1.387E-07	1.092E+10	1.116E+10	-6.927E-01	6.342E-01	1.544E-04
15	1.053E+01	9.868E+00	1.600E-02	9.178E-02	1.188E-07	1.344E-07	1.084E+10	1.135E+10	-6.946E-01	6.336E-01	2.261E-03
16	1.055E+01	9.894E+00	1.600E-02	9.419E-02	1.174E-07	1.306E-07	1.089E+10	1.144E+10	-6.946E-01	6.329E-01	-7.581E-04
17	1.078E+01	9.790E+00	1.600E-02	9.585E-02	1.165E-07	1.292E-07	1.119E+10	1.130E+10	-6.732E-01	6.423E-01	2.570E-06
18	9.956E+00	9.883E+00	1.600E-02	9.579E-02	1.151E-07	1.287E-07	1.054E+10	1.141E+10	-8.970E-01	6.473E-01	4.725E-03

ADORE Execution Problems

Equation ID – Examine Ball/Race Slip and Traction

- Traction Curve
  - Hypothetical due to low lubricant film for most of the slip range
  - However note high peak in EHD traction near zero slip

1b. Traction Curves for Rolling Element #18

Slide/Roll	.....Trac Coeff......		...Isothermal Film... (m)		...Thermal Rec Fac...		......Net Film....... (m)	
	Outer Race	Inner Race	Outer Race	Inner Race	Outer Race	Inner Race	Outer Race	Inner Race
0.000E+00	0.000E+00	0.000E+00	3.165E-06	2.929E-06	3.641E-02	4.466E-02	1.152E-07	1.308E-07
3.923E-03	1.735E-02	7.293E-01	3.165E-06	2.929E-06	3.578E-02	4.390E-02	1.132E-07	1.286E-07
7.846E-03	2.000E-02	4.809E-01	3.165E-06	2.929E-06	3.531E-02	4.332E-02	1.117E-07	1.269E-07
1.177E-02	1.914E-02	3.717E-01	3.165E-06	2.929E-06	3.489E-02	4.281E-02	1.104E-07	1.254E-07
1.569E-02	1.794E-02	1.800E-02	3.165E-06	2.929E-06	3.450E-02	4.233E-02	1.092E-07	1.240E-07
1.962E-02	1.708E-02	1.713E-02	3.165E-06	2.929E-06	3.414E-02	4.189E-02	1.080E-07	1.227E-07
2.354E-02	1.656E-02	1.660E-02	3.165E-06	2.929E-06	3.379E-02	4.147E-02	1.069E-07	1.215E-07
2.746E-02	1.628E-02	1.631E-02	3.165E-06	2.929E-06	3.346E-02	4.106E-02	1.059E-07	1.203E-07
3.139E-02	1.614E-02	1.615E-02	3.165E-06	2.929E-06	3.315E-02	4.068E-02	1.049E-07	1.192E-07
3.531E-02	1.607E-02	1.607E-02	3.165E-06	2.929E-06	3.285E-02	4.031E-02	1.040E-07	1.181E-07
3.923E-02	1.603E-02	1.604E-02	3.165E-06	2.929E-06	3.256E-02	3.995E-02	1.030E-07	1.170E-07
4.316E-02	1.601E-02	1.602E-02	3.165E-06	2.929E-06	3.227E-02	3.961E-02	1.021E-07	1.160E-07
4.708E-02	1.601E-02	1.601E-02	3.165E-06	2.929E-06	3.200E-02	3.928E-02	1.013E-07	1.151E-07
5.100E-02	1.600E-02	1.600E-02	3.165E-06	2.929E-06	3.174E-02	3.895E-02	1.004E-07	1.141E-07
5.492E-02	1.600E-02	1.600E-02	3.165E-06	2.929E-06	3.148E-02	3.864E-02	9.963E-08	1.132E-07
5.885E-02	1.600E-02	1.600E-02	3.165E-06	2.929E-06	3.123E-02	3.834E-02	9.884E-08	1.123E-07
6.277E-02	1.600E-02	1.600E-02	3.165E-06	2.929E-06	3.099E-02	3.804E-02	9.808E-08	1.114E-07
6.669E-02	1.600E-02	1.600E-02	3.165E-06	2.929E-06	3.075E-02	3.775E-02	9.733E-08	1.106E-07
7.062E-02	1.600E-02	1.600E-02	3.165E-06	2.929E-06	3.052E-02	3.747E-02	9.660E-08	1.098E-07
7.454E-02	1.600E-02	1.600E-02	3.165E-06	2.929E-06	3.030E-02	3.719E-02	9.589E-08	1.090E-07

ADORE Execution Problems

Termination due to error count

- Examine error propagation

```
Encountered error code:   101      Supplementary code:     0

    Truncation limit encountered

    Step, subStep numbers and Equation ID are:
       313      0    119

    Current Step Size and Truncation Error are:
      5.0000E-03  1.8438E-03  <<<<<<<<<<<<

    Execution terminated due to error count.


Encountered error code:   101      Supplementary code:     0

    Truncation limit encountered

    Step, subStep numbers and Equation ID are:
       312      0    119

    Current Step Size and Truncation Error are:
      5.0000E-03  2.8531E-03  <<<<<<<<<<<<
```

ADORE Execution Problems

Termination due to error count

- Examine error propagation

```
Encountered error code:  101     Supplementary code:     0

    Truncation limit encountered

    Step, subStep numbers and Equation ID are:
       311      0    119

    Current Step Size and Truncation Error are:
      5.0000E-03   4.1605E-03  <<<<<<<<<<<<<

Encountered error code:  101     Supplementary code:     0

    Truncation limit encountered

    Step, subStep numbers and Equation ID are:
       310      0    119

    Current Step Size and Truncation Error are:
      5.0000E-03   4.3606E-02  <<<<<<<<<<<<<

Encountered error code:  101     Supplementary code:     0

    Truncation limit encountered

    Step, subStep numbers and Equation ID are:
       309      0    119

    Current Step Size and Truncation Error are:
      5.0000E-03   2.2767E-03  <<<<<<<<<<<<<
```

ADORE Execution Problems

Conclusions from Diagnostic Messages

- Numerical
  - Error propagation marginally divergent
  - Reducing the minimum step size may take the solution bit further
- Physical
  - The bearing has a lubrication problem under prescribed operating condition
  - Operation is on negative part of traction curve

ADORE Execution Problems

Conclusions from Diagnostic Messages

- Current problem due to input hypothetical traction curve
  - Input modification may be fix the problem
- Similar situation may be encountered under well lubricated conditions
  - Traction model modifications may be necessary
  - More realistic traction data to avoid any extrapolation
  - Possible visco-elastic modeling
  - Change of lubricant or operating conditions

ADORE Technical Seminar

Part 1: Program Description and Capabilities

Part 2: Input Data and File System Management

Part 3: Program Output and User Applications

- ADORE Print Output
- ADORE Plot Output
- Graphics Animation - AGORE

  Break

- Critical Performance Parameters
- Computing effort optimization
- Summary
- Discussion

  Break

- User Applications and General Discussion

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Recommendations for Additional Technical Support

- Adore user seminar
  - Adore overview
  - Input/Output
  - Three days effort
- Adore development seminar
  - Analytical formulations
  - Code development and architecture
  - One week effort
- Customized Support
  - Adore extended technical support unit

Recommendations for NASA/Glenn

- Annual ADORE Update and Maintenance
  - Adore Opt-U
  - All updates during service period
  - Minor technical support via phone or email
- ADORE Extended Technical Support
  - Adore Opt-S1 – Three weeks effort per unit
  - Customized support to model bearing problems
  - Technical assistance in problem diagnosis and simulation
  - Adore Opt-S2 – Travel associated with Opt-S1
  - On site support as and when required