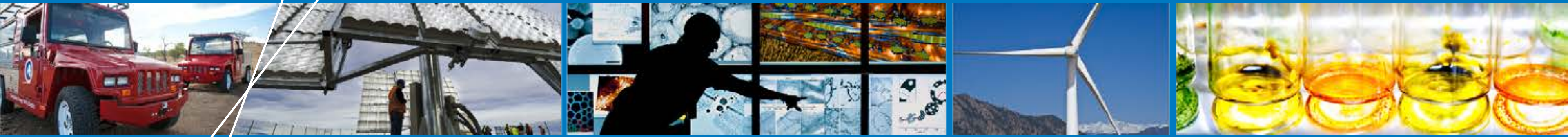
Rolling Element Bearing Stiffness Matrix Determination



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Motivation

- **Limited work on stiffness matrix in the literature**
  - Diagonal matrix approximation typically used
- **Elastic deformation of race causes nondiagonal terms**

$$
\begin{bmatrix}
k_{xx} & k_{xy} & k_{xz} & k_{x\theta_x} & k_{x\theta_y} & 0 \\
 & k_{yy} & k_{yz} & k_{y\theta_x} & k_{y\theta_y} & 0 \\
 & & k_{zz} & k_{z\theta_x} & k_{z\theta_y} & 0 \\
 & & & k_{\theta_x\theta_x} & k_{\theta_x\theta_y} & 0 \\
 & \mathit{Symmetric} & & & k_{\theta_y\theta_y} & 0 \\
 & & & & & 0
\end{bmatrix}
$$

Coupling between the radial and rotational displacement

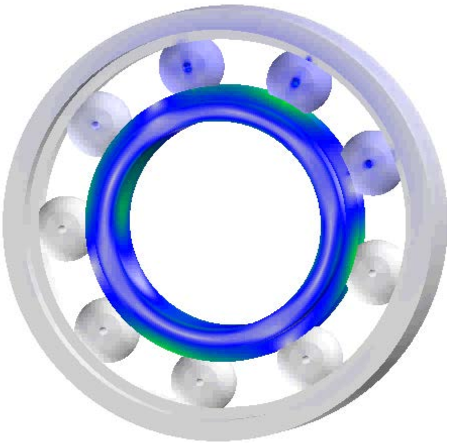
Coupling between the axial and rotational displacement

Coupling between the axial and radial displacement

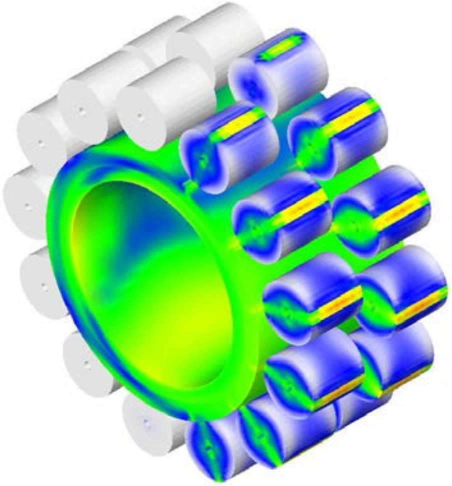
Finite Element/Contact Mechanics Model

- **Three-dimensional finite element model includes microgeometry**
- **Analyze contact between rolling elements and races**
  - Contact searched at every time instant as bearing rotates

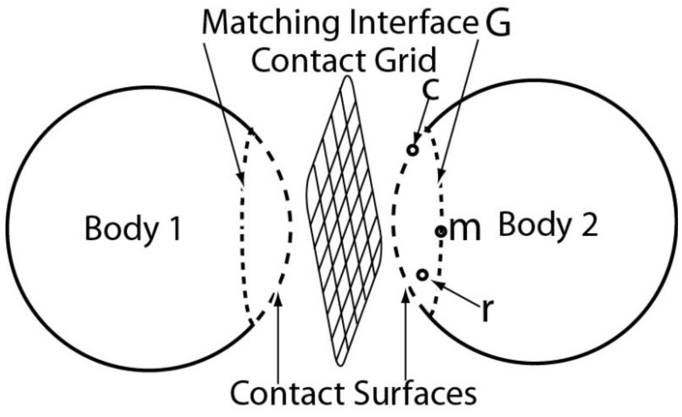
Radial Ball Bearing



Cylindrical Bearing



Contact Grid



Accuracy Order of Finite Element Analysis

- **Numerical Jacobian used to compute K**
- **Order of Jacobian approximation formula should be comparable to the accuracy order of finite element analysis (FEA)**
- **Method to obtain the accuracy order of FEA**

$$V_h = V + \underbrace{c_1 h^{p_1} + c_2 h^{p_2} + \dots}_{e_h}$$

$$\frac{e_{h_3} - e_{h_2}}{e_{h_2} - e_{h_1}} = \frac{V_{h_3} - V_{h_2}}{V_{h_2} - V_{h_1}} \approx \frac{h_2^{p_1} - h_3^{p_1}}{h_1^{p_1} - h_2^{p_1}}$$

$$p_1 = \frac{log\{(\frac{V_{h_3} - V_{h_1}}{V_{h_3} - V_{h_2}})\frac{log\frac{h_2}{h_3}}{log\frac{h1}{h3}}\}}{log(\frac{h_1}{h_2})}$$

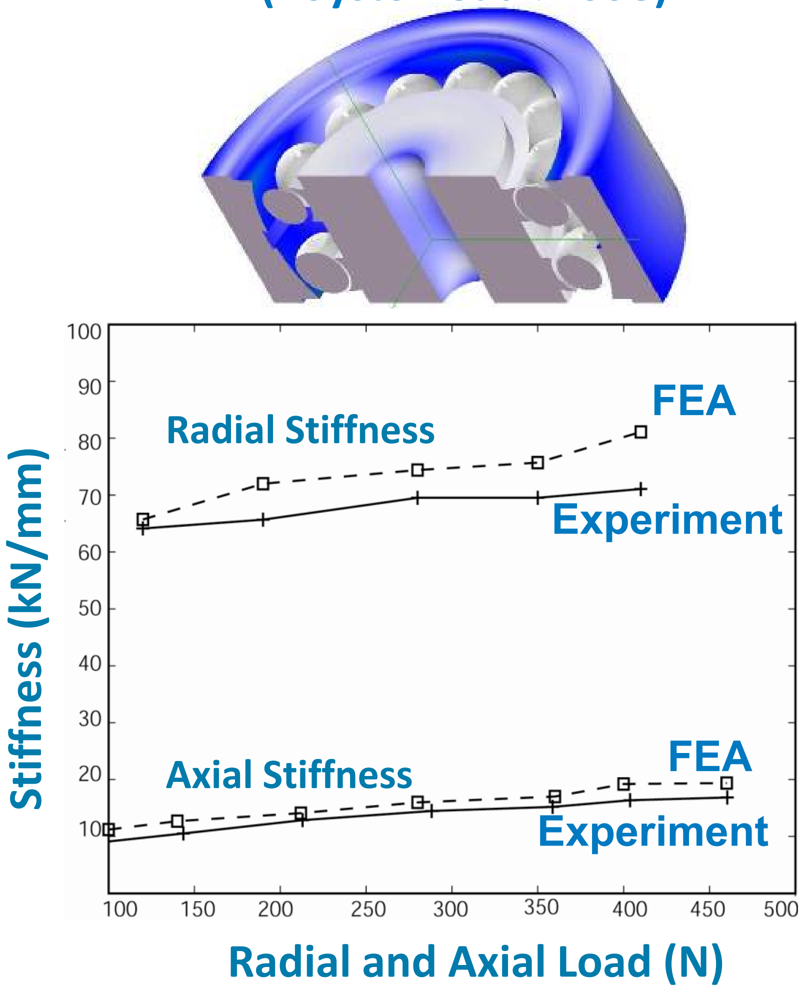
V_h : finite element solution
V : exact solution
h : finite element size
p_1 : order of accuracy

Accuracy Order	FEA	FEA/Contact
p1	1.11	1.94

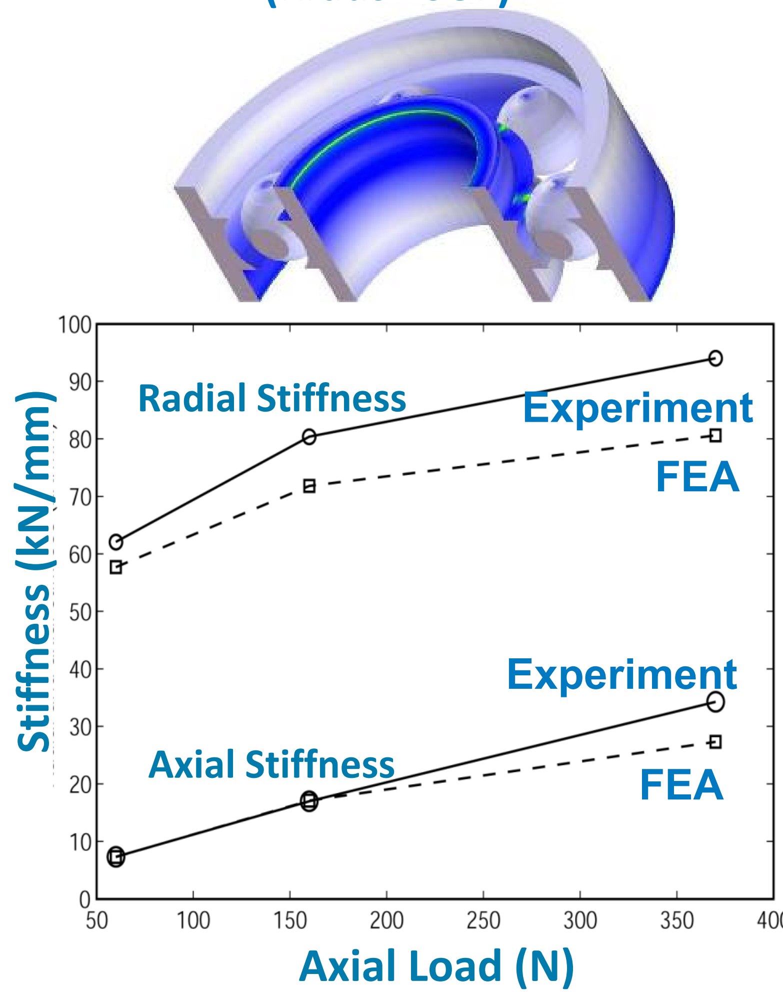
Comparison Against Published Experiments

- **Calculated stiffnesses by FEA agree with experiments**

(Royston et al. 1998)

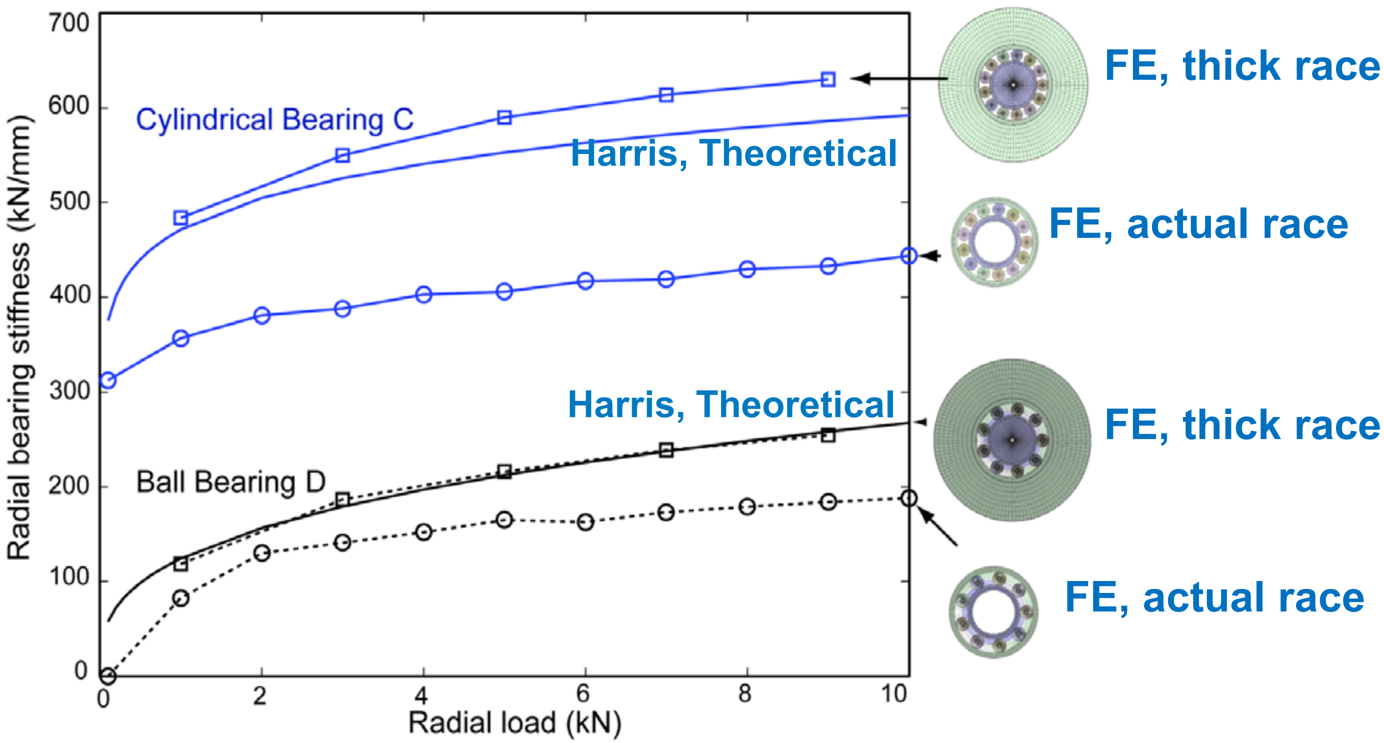


(Kraus 1987)



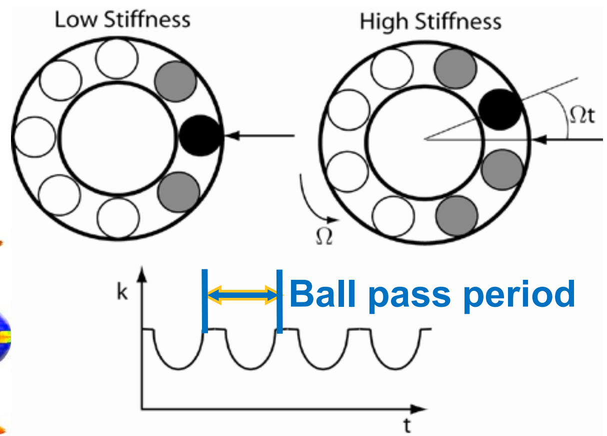
Comparison Against Theoretical Models

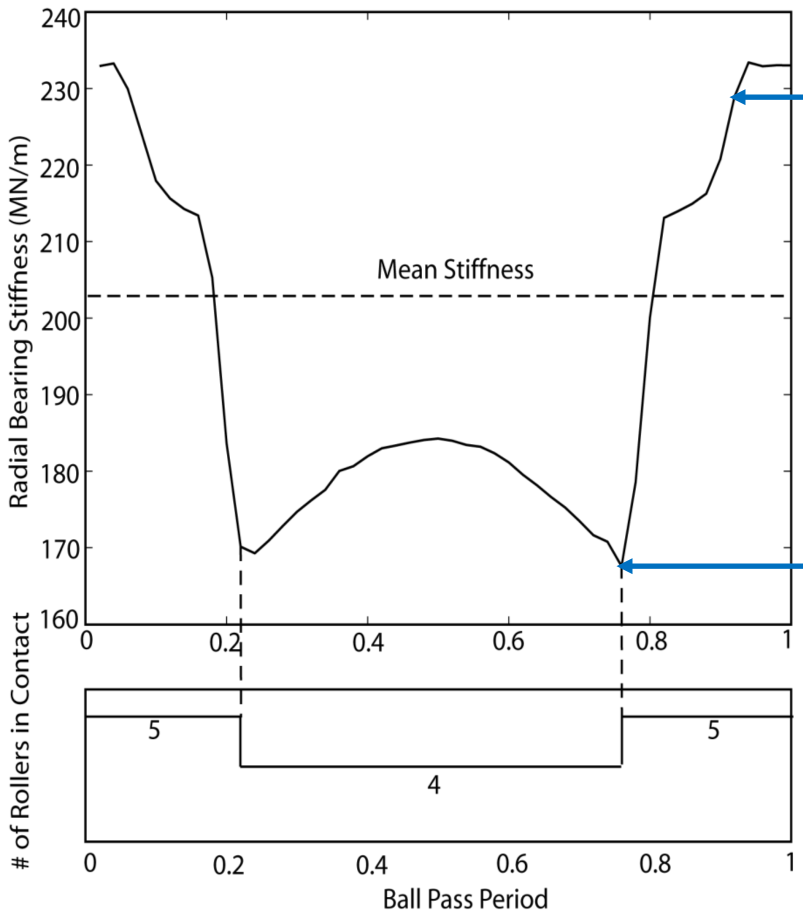
- **FEA stiffness agrees with the theoretical model**
  - **Only with unrealistic races that match Harris's assumptions**
- **Theoretical models predict higher stiffness with design dimensions**

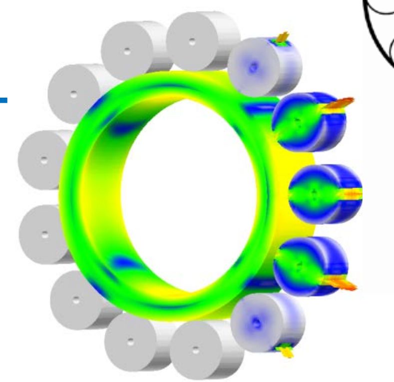


Bearing Stiffness Is Time-Varying

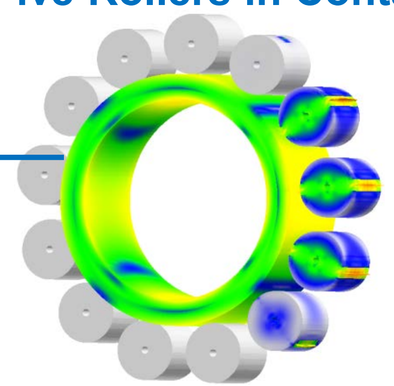
- **Number of rollers in contact changes periodically**
- **Can excite gearbox vibration**







Five Rollers in Contact



Four Rollers in Contact

Off-Diagonal Stiffnesses Affect Gear Vibration

- **Gear dynamics with off-diagonal stiffnesses differ from gear dynamics with a diagonal stiffness matrix**
  - Need to include off-diagonal stiffnesses

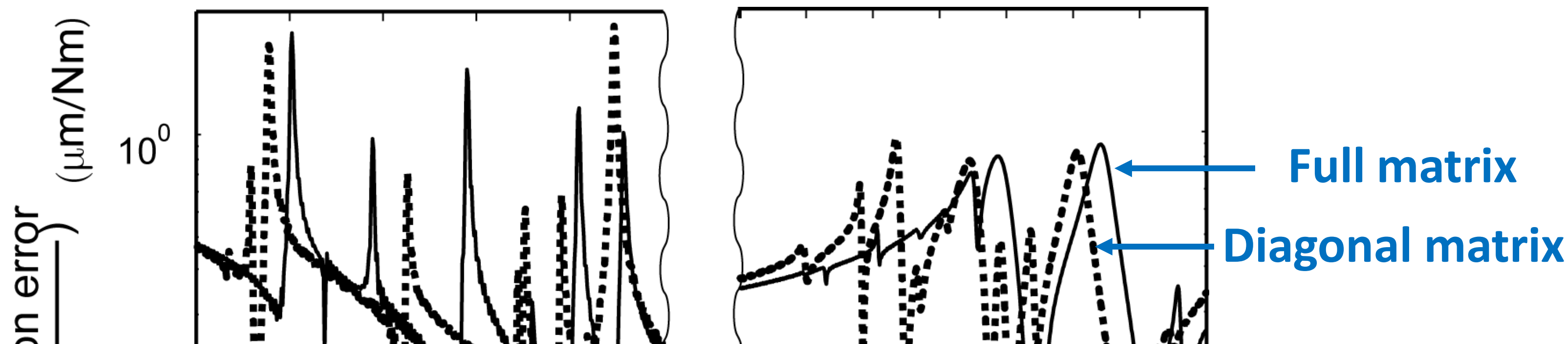


Photo by Yi Guo, NREL

Conclusions

- A method developed to determine bearing stiffness matrices
- Method validated by experiments
- Comparison against theoretical models expose their limitations
- Bearing contact is nonlinear and time-varying
- Bearing microgeometry affects stiffness
- Off-diagonal bearing stiffnesses affect gear dynamics

Thank You!

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