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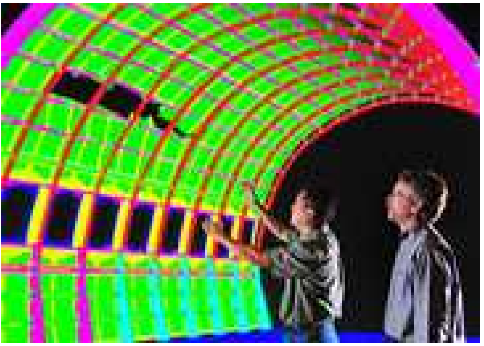
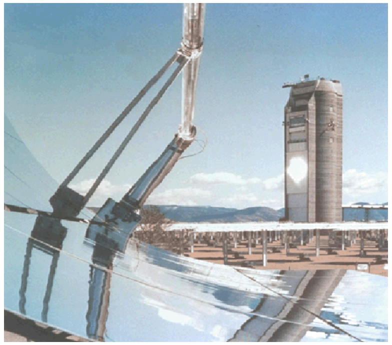
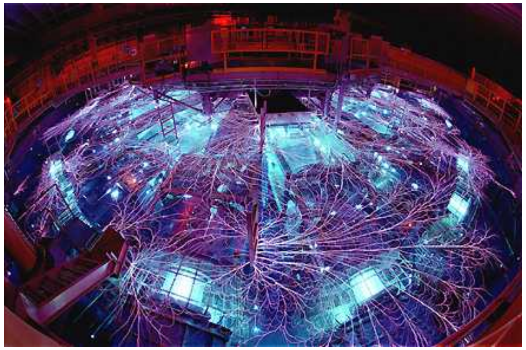
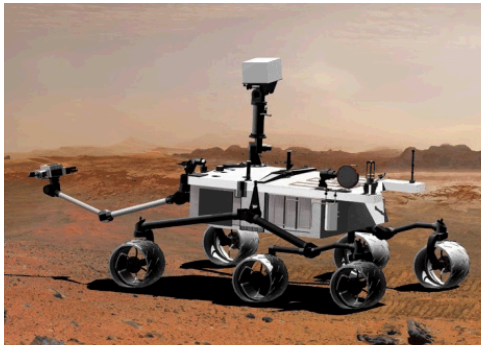

The Effect of the Contact Model on the Design of Mechanical Systems

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U.S. DEPARTMENT OF ENERGY

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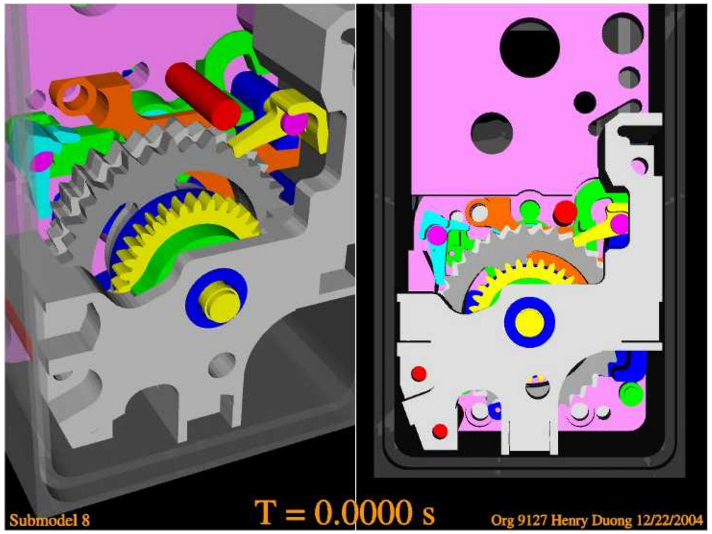
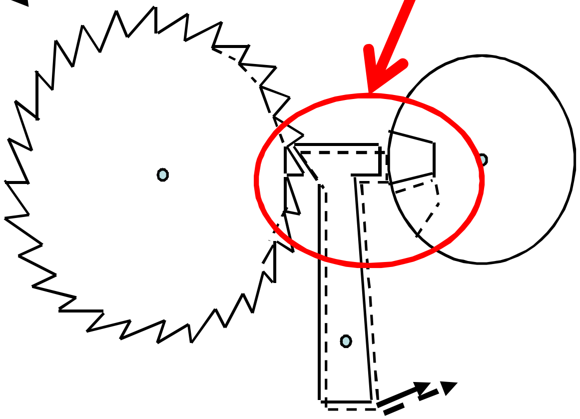
Predicting Vibro-Impact Response



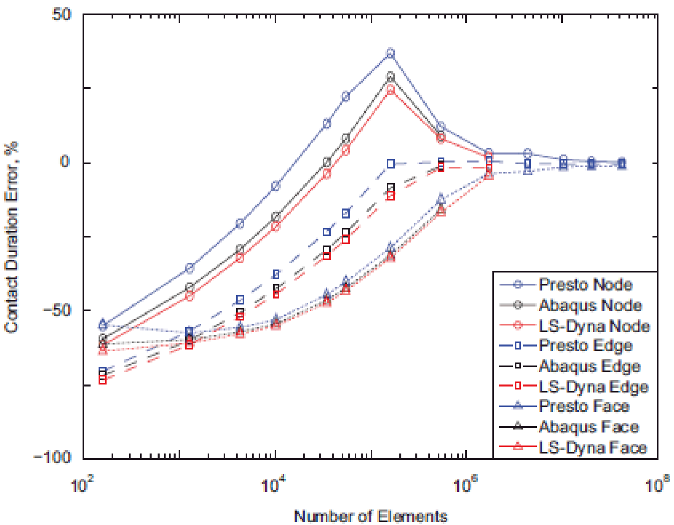
- Motivation
- Constitutive Models
- Example of a representative system

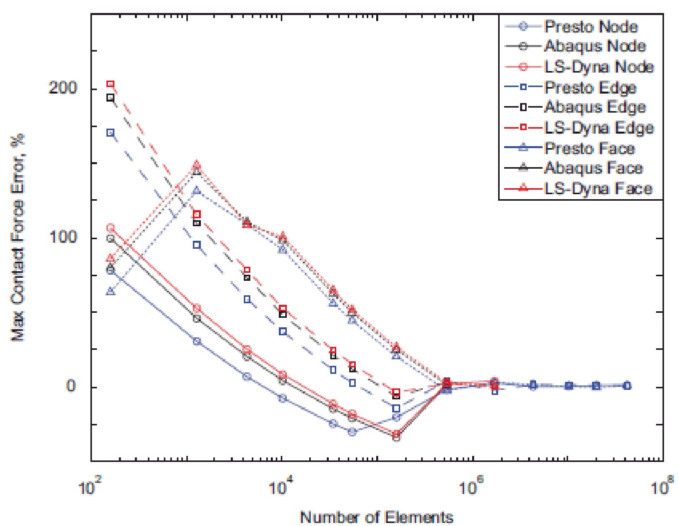
Key impact events



Contact is Ubiquitous in Mechanisms

- Contact is a phenomenon that occurs both externally and internally between components
- Central question: How should contact be modeled?
- High Fidelity FEA simulations can be prohibitively expensive to <u>accurately</u> model contact…





FEA studies of elastic contact compared to the exact, Hertzian solution…

Two Competing Views

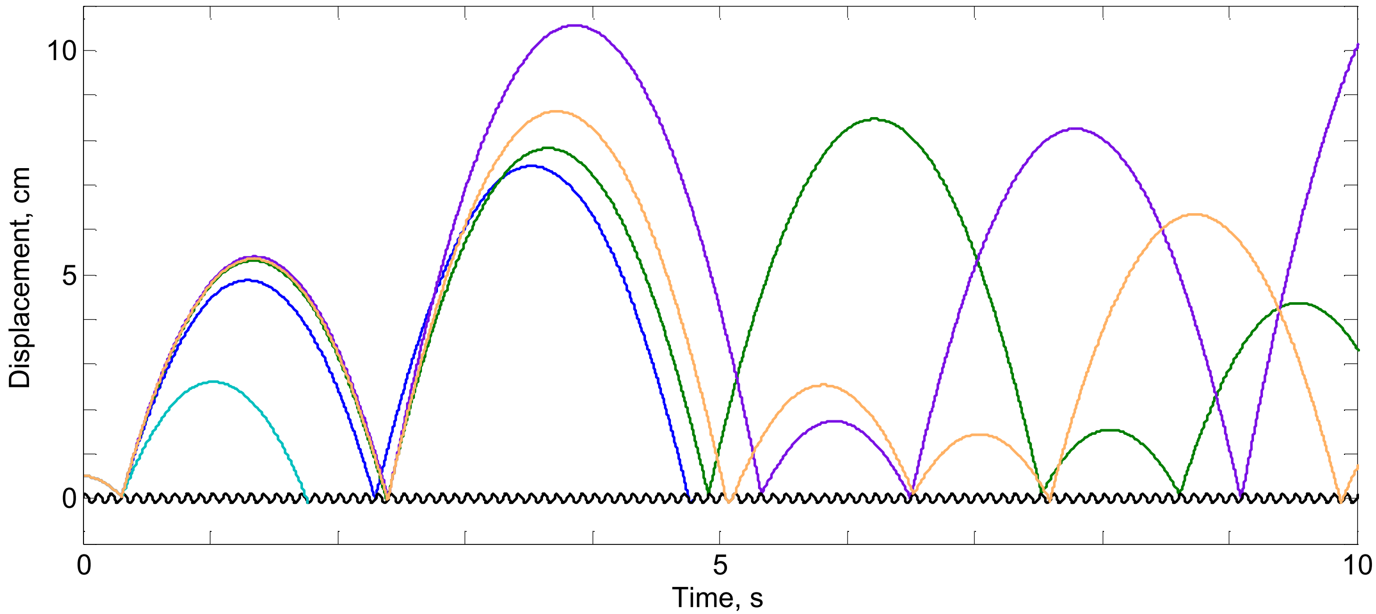
- In the literature, two competing viewpoints:

1. As long as impacts are modeled in a realistic manner, the responses are qualitatively the same

2. Because contact is a nonlinear phenomenon, small differences in the model can lead to large differences in the response

Characteristics of Nonlinear Systems

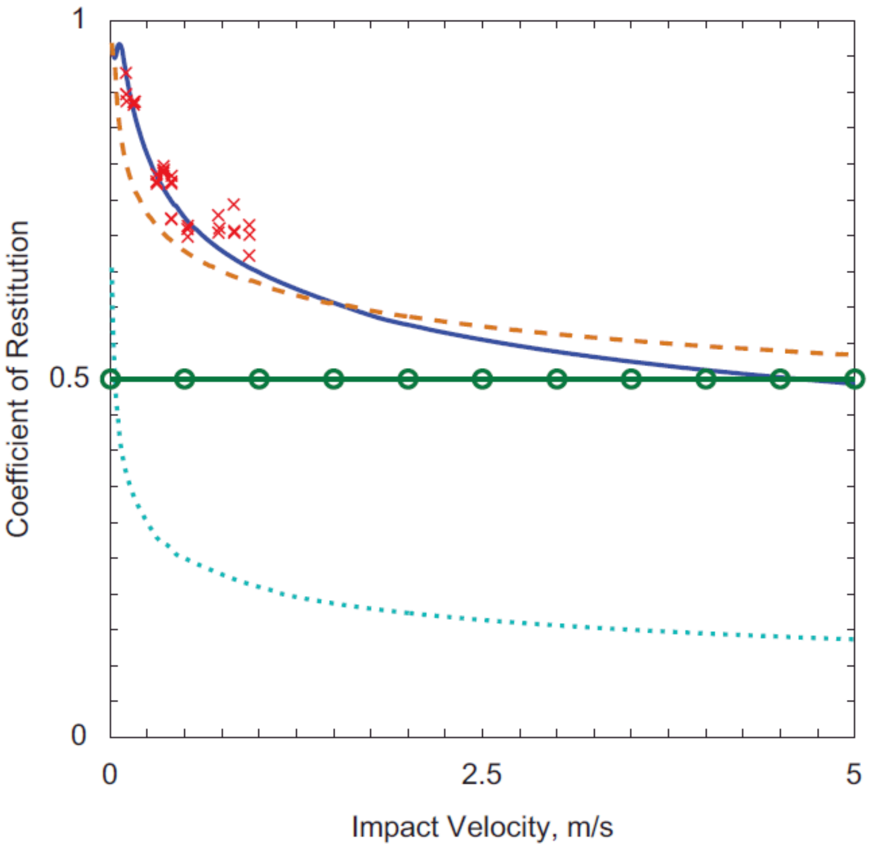
- Rigid body simulations often model contact in an ad hoc manner
- Presence of contact makes systems nonlinear – by definition, small changes in the modeling method can lead to large changes in the response



Shown: coefficient of restitution (green), Piecewise-Linear (purple), Brake's elastic-plastic (blue), a similar elastic plastic (orange), and a dissimilar elastic plastic (cyan)

Constitutive Models

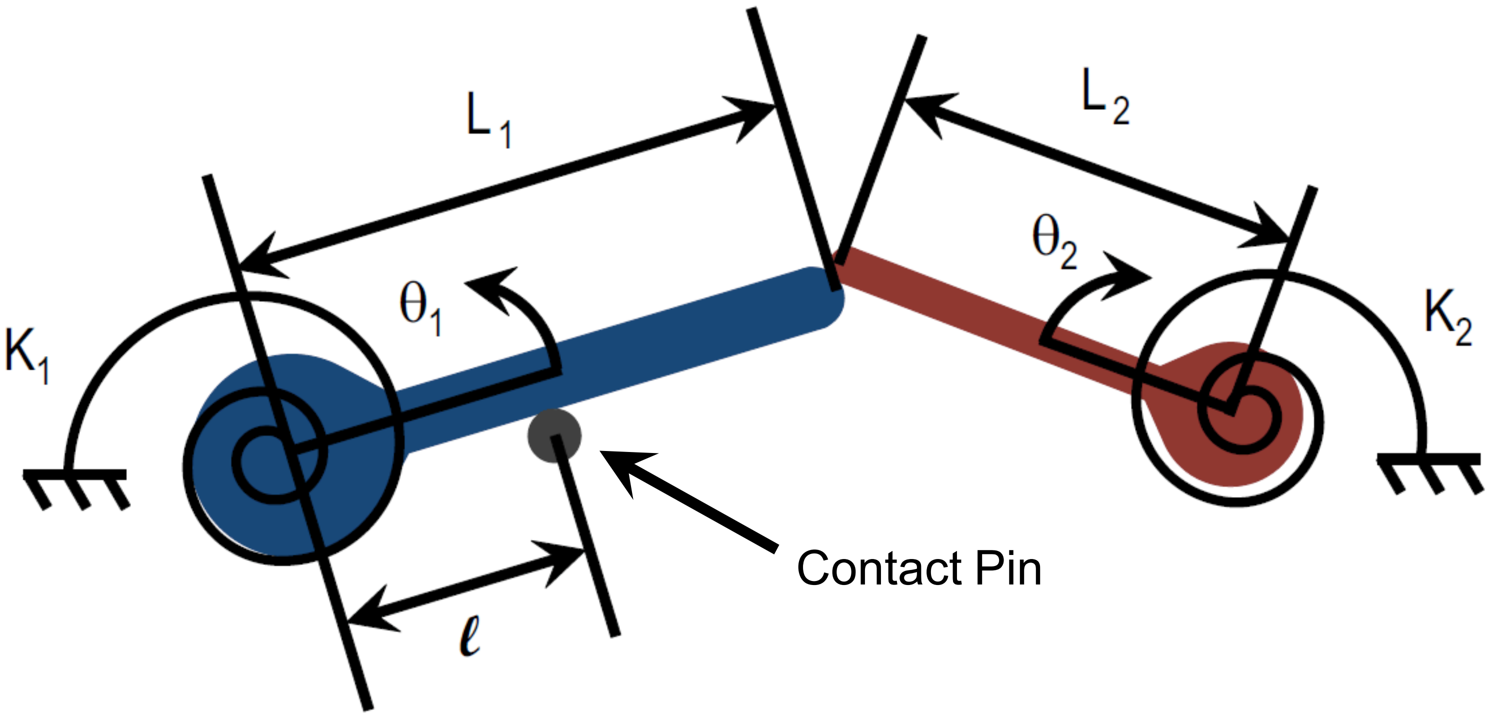
Four contact models considered:



x: measured coefficients of restitution, (Brake et al., 2011)

- Coefficient of restitution (green)
- EP1: Elastic-perfectly plastic developed in (Brake, 2012) (blue)
- EP2: A similar elastic-plastic model developed in (Etsion et al., 2005) (orange)
- EP3: A dissimilar elastic-perfectly plastic model developed in (Thornton, 1997) (cyan)
- Coefficient of restitution model tuned to match model EP1 at 5 m/s (a typical impact velocity in the simulations)

Two Pawl System



- Contact is modeled between pawl 1 (left) and the constraining pin, as well as between both pawls.
- Pawls mounted on frictionless shafts at location of torsional spring attachment.

State Space Representation

- Free flight has a closed form solution
- In contact directly solved via an IMEX method
- Base excitation of shafts modeled as haversine impulse
- Representative of mechanical subsystems used in component designs
- Contact force defined to be zero out of contact, and determined by contact model during contact

$$\begin{Bmatrix} \dot{\theta}_1 \\ \ddot{\theta}_1 \\ \dot{\theta}_2 \\ \ddot{\theta}_2 \end{Bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -K_1/J_1 & -c_1/J_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -K_2/J_2 & -c_2/J_2 \end{bmatrix} \begin{Bmatrix} \theta_1 \\ \dot{\theta}_1 \\ \theta_2 \\ \dot{\theta}_2 \end{Bmatrix} + \begin{Bmatrix} 0 \\ \frac{F_2\ell - F_1 L_1 + T_1 + K_1 P_1}{J_1} \\ 0 \\ \frac{F_1 L_2 + T_2 + K_2 P_2}{J_2} \end{Bmatrix}$$

Contact between pawls:

$$F_1 = F_C(\theta_1 L_1 - \theta_2 L_2, \dot{\theta}_1 L_1 - \dot{\theta}_2 L_2)$$

Contact between pawl 1 and constraint pin:

$$F_2 = F_C(-\theta_1 \ell, -\dot{\theta}_1 \ell),$$

Some Quantities of Interest

- Wear work rates:

$$\chi_j = \frac{1}{T_{Cj}} \int_{t_j}^{t_j+T_{Cj}} \left\| F_C(|x| - \ell, \mathrm{sign}(x)\dot{x}(t))\dot{x}(t) \right\| dt$$

$$\chi = \frac{1}{N} \sum_{j=1}^{N_C} \chi_j$$

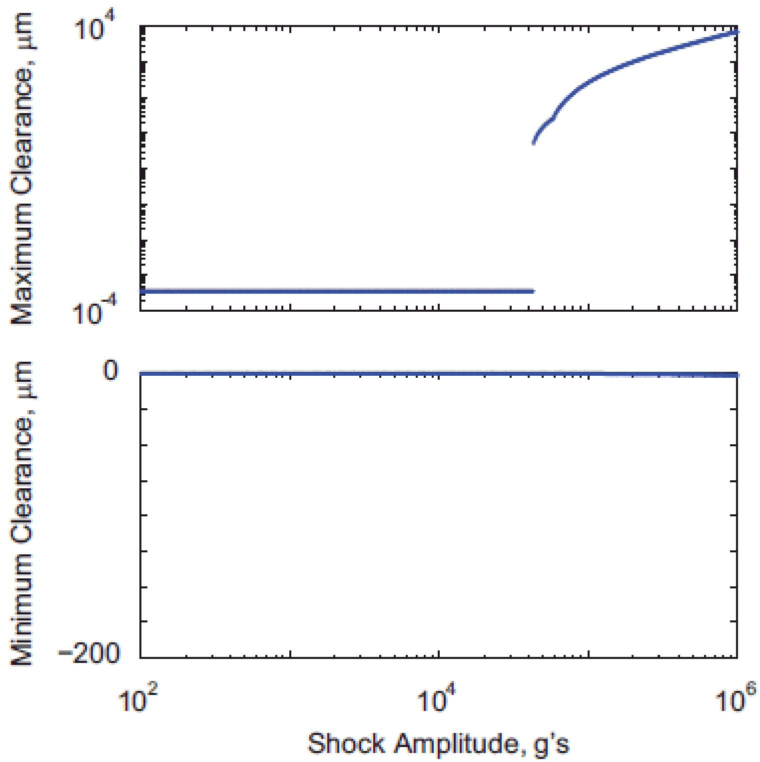
N Number of periods

N_C Number of impacts

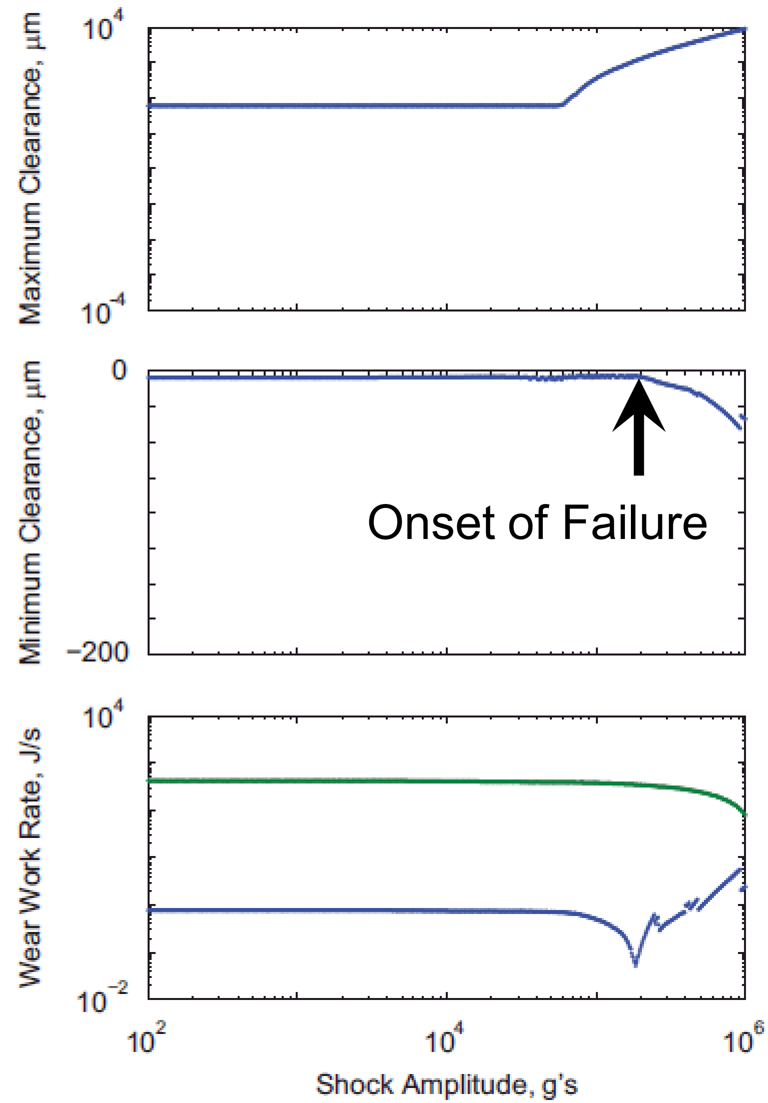
- Clearances:
  - A large negative clearance implies pawl 2 rotates below pawl 1. <u>This is defined to be a device failure.</u>
  - A small negative clearance implies permanent, plastic deformation.
  - Maximum clearances indicate shock severity.

Sensitivity to Shock Amplitude

Coefficient of Restitution

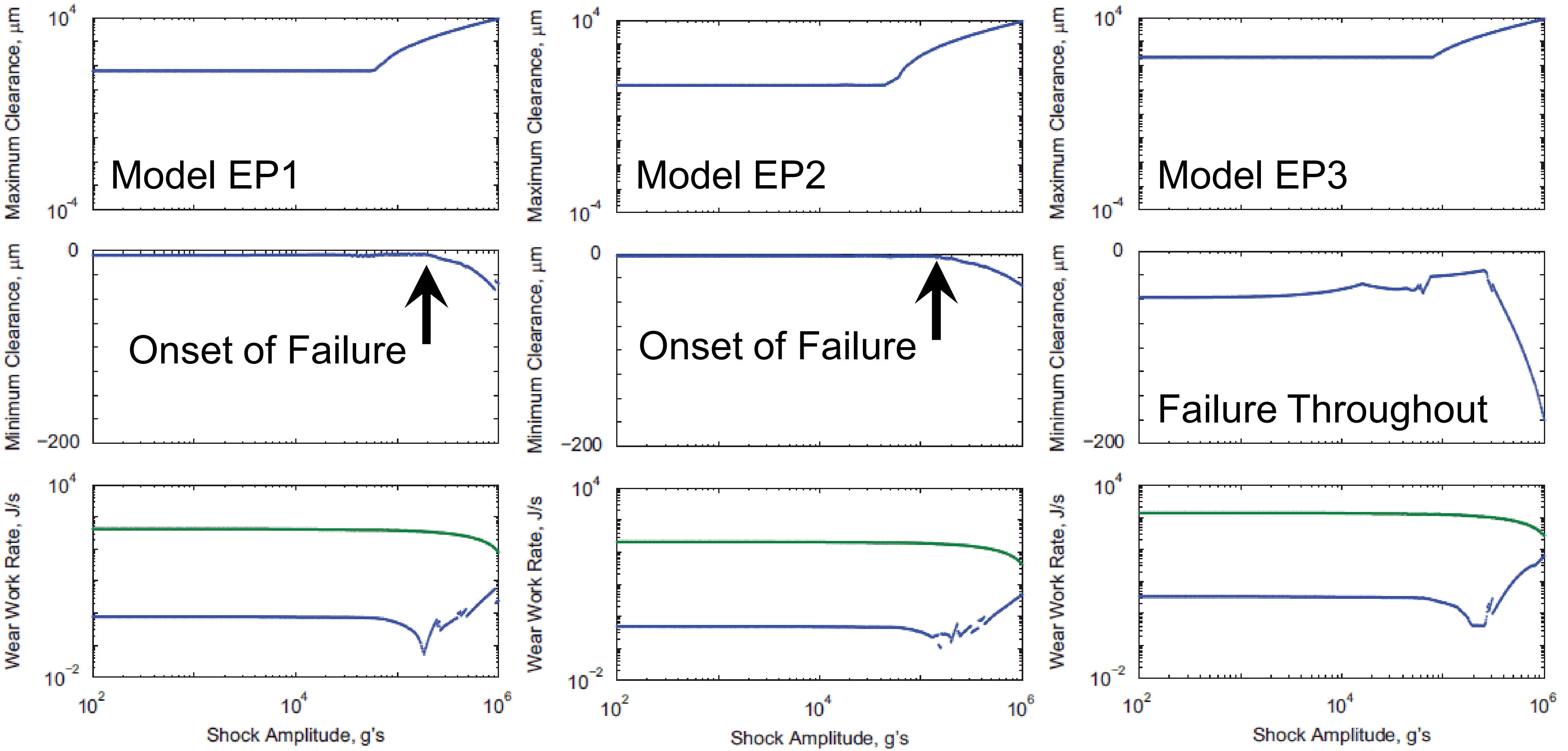


Model EP1



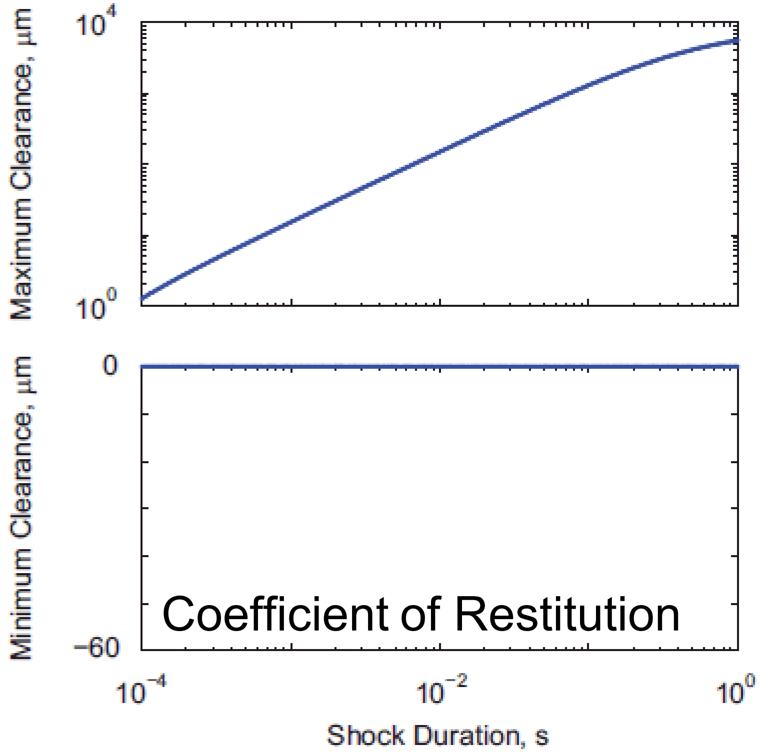
- Shock duration of 1 ms.
- Qualitatively different responses at low amplitudes.
- The CoR is not amenable to calculating wear, and predicts no failures.
- Model EP1: Failure at 0.2 Mg's

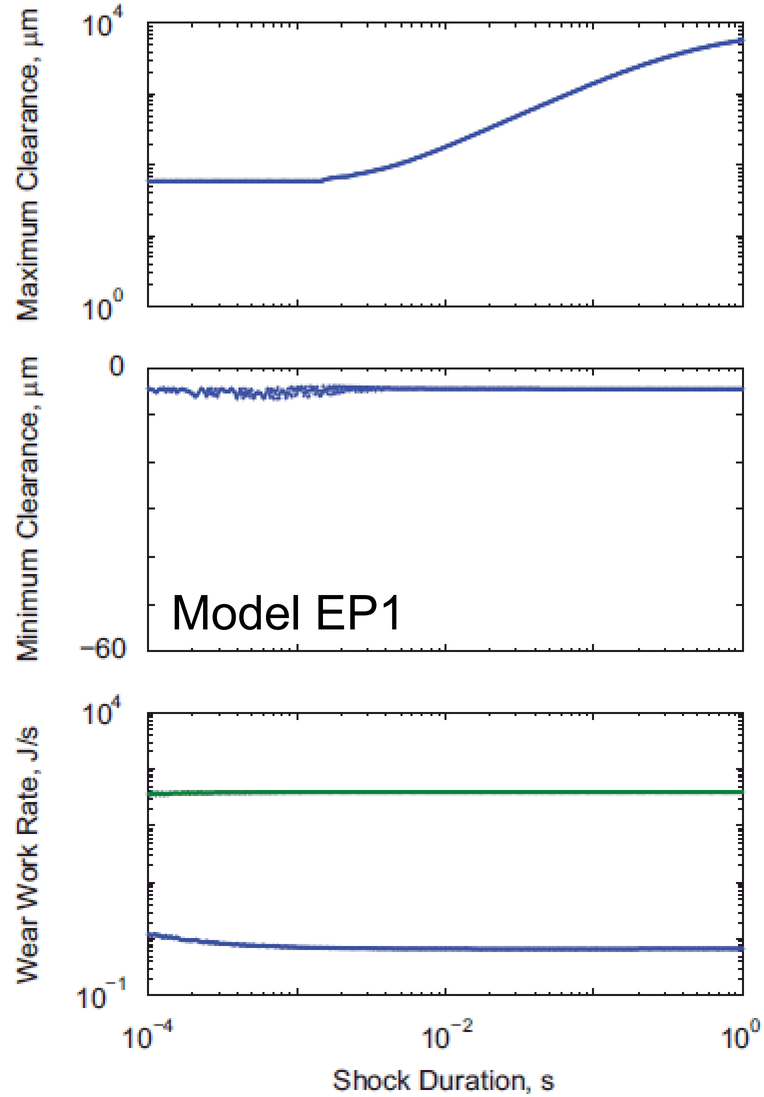
Sensitivity to Shock Amplitude



- Models EP1 and EP2 predict
- Model EP2: Failure at 0.15 Mg's
- Model EP3: Failure throughout, 3-10x higher wear work rates

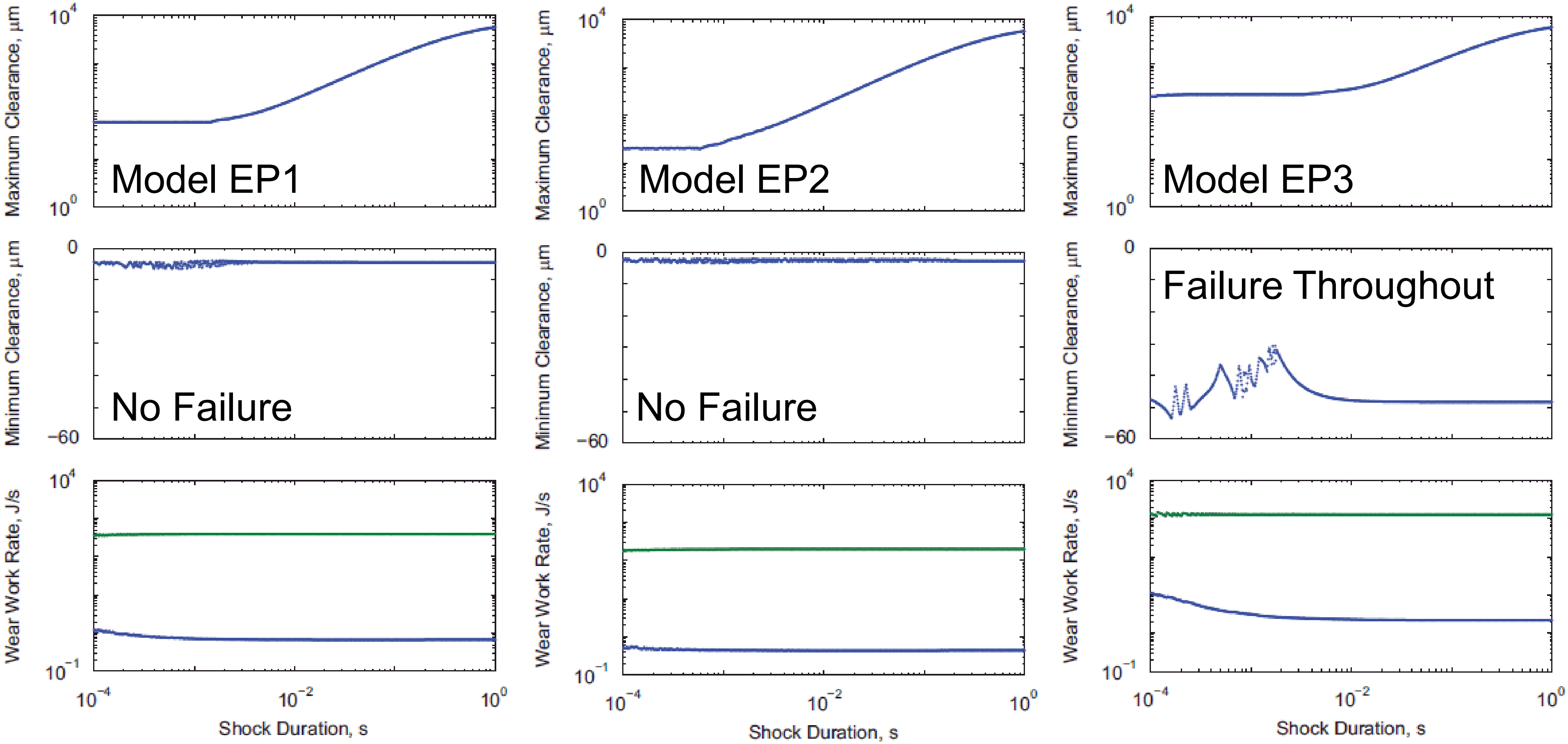
Sensitivity to Shock Duration





- Shock amplitude of 50 kg's
- Qualitatively different responses at short shock durations, though similarities at high durations

Sensitivity to Shock Duration



- Qualitative agreement seen between models EP1 and EP2.
- Model EP3 predicts failure at all shock durations, and significantly higher wear work rates.

Summary and Conclusions

- Qualitatively different responses of the maximum clearance seen for short shock durations and low shock amplitudes; however, for high amplitudes and long durations, the differences are lost in the noise.
- **Predictions of device failure extremely sensitive to contact model**:
  - The coefficient of restitution model predicts no failures
  - Model EP3 (a simplified elastic plastic model) predicts all failures
- Wear work rates (indicative of damage and fatigue) highly dependent on contact model, and vary by an order of magnitude.
- Use of the coefficient of restitution or other simplified contact model can lead to significantly misestimating the severity of an excitation
- Recommendation: an impact model validated for the type of contact in a system should be used in order to have accurate assessments of wear, damage, and severity