

Materials & Advanced Manufacturing (M&AM)

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GROUND VEHICLE SYSTEMS ENGINEERING & TECHNOLOGY SYMPOSIUM
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NDIA
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Modeling of Shear Thickening Fluids for Analysis of Energy Absorption Under Impulse Loading

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- Introduction
 - Motivation
 - Shear Thickening Fluids
 - Objectives
- Microscale Model
 - Shear Thickening Mechanisms
 - Discrete Element Method (DEM)
 - Results
- Macroscale Model
 - Reverberation Matrix Method (RMM)
 - Results
- Conclusions
- Future Work





- Developing lightweight structures that provide occupant safety and structural durability is critical for future military vehicles
- Multilayer plates allow for optimization of material properties
- Damping mechanisms between layers should improve shock absorption
 - Shear thickening fluids (STFs) possible damping mechanism

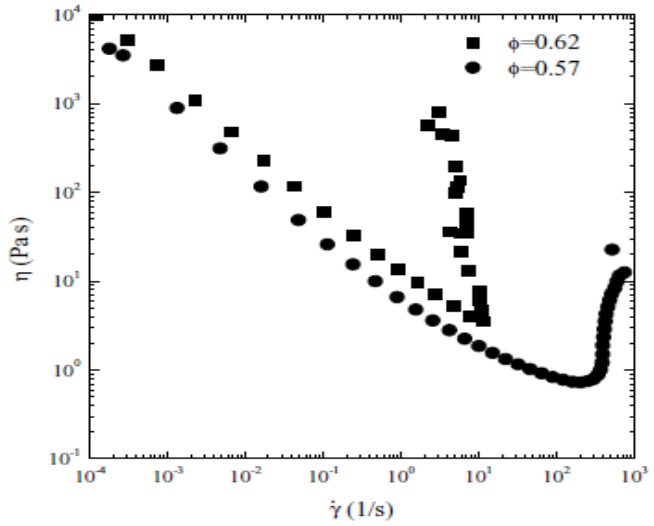


Examples of Multilayer Plates

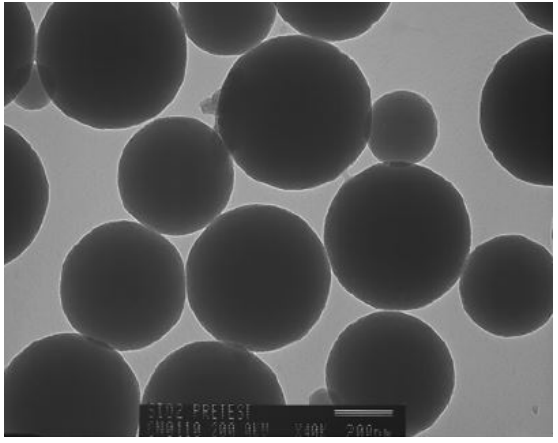




- Non-Newtonian fluids
 - Viscosity increases as shear rate increases
- Comprised of a fluid phase saturated with colloidal particles
- Possible damping mechanism in impulse loading



Viscosity v Shear Rate

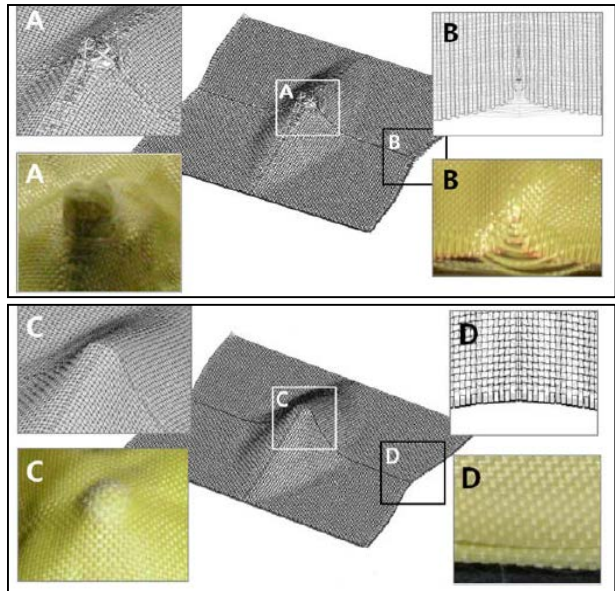


Electron Microscopy of Silica Particles [2]

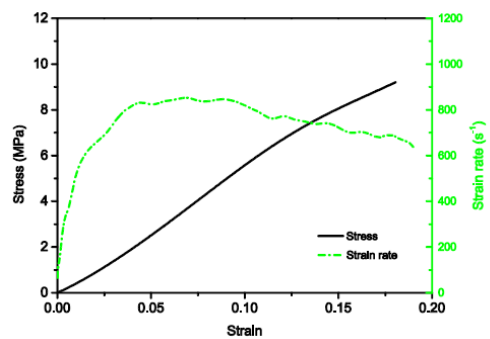
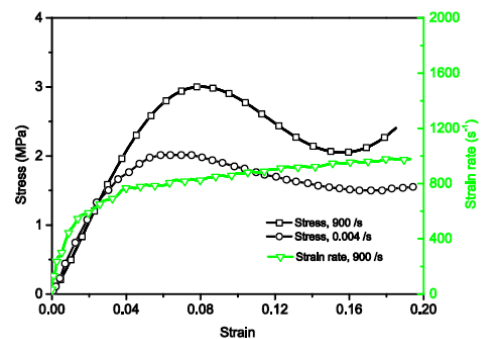




- STFs have been used for a variety of energy absorbing applications
 - Kevlar body armor, sandwich structures, batteries



Ballistic Results for Regular and STF Impregnated Kevlar [2]



Stress-Strain Results for Empty and Filled Sandwich Structure[4]



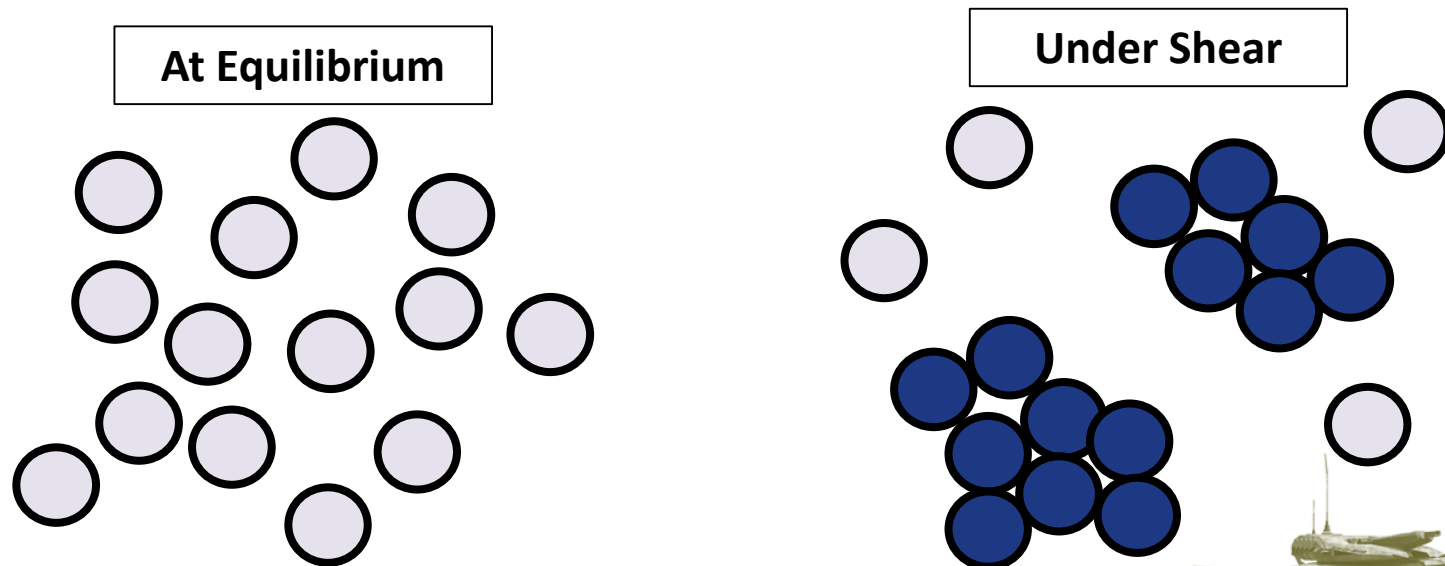


- Develop microscale model of shear thickening fluid
 - Capture shear thickening behavior
- Extract relationship between viscosity and shear rate
- Implement material properties into reduced order macroscale model





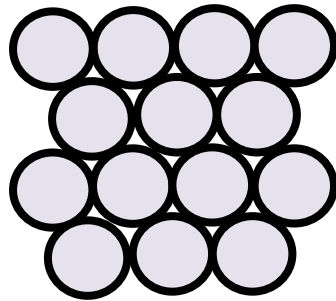
- Hydroclusters
 - Particles pushed together into clusters during shear
 - Increased lubrication drag forces between clusters
 - Lubrication forces- hydrodynamic pressure in fluid being squeezed out between two solid surfaces



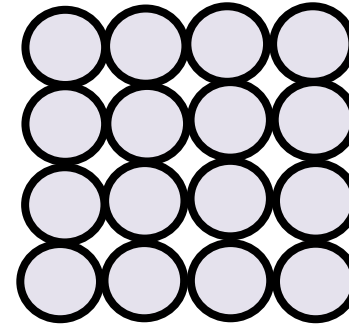


- Dilatancy
 - Bulk volume of particles increases under shear due to particles not being able to slide past each other
 - Results in particles pushing on boundaries and stress from inter-particle friction
 - Granular material behavior

At Equilibrium



Under Shear

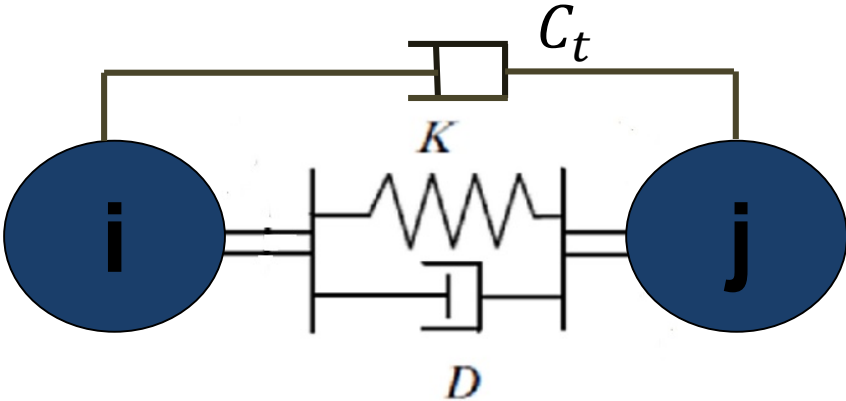


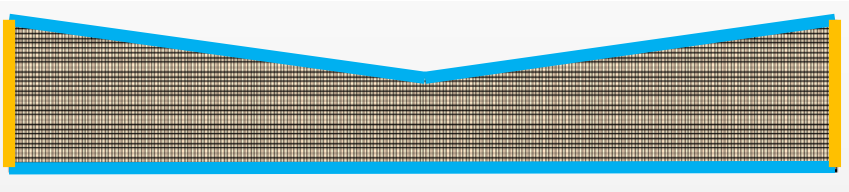
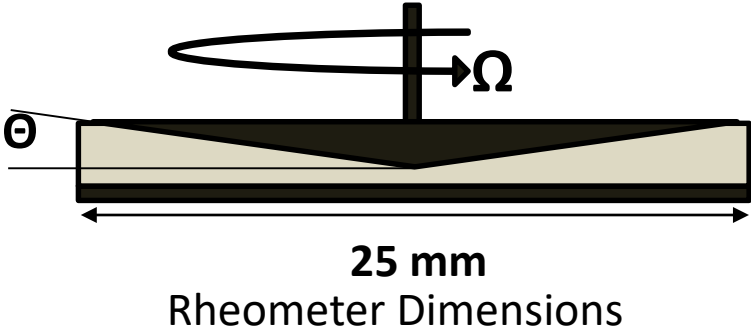


- Meshless, Lagrangian method used to model particles
 - Allows for particles and fluid phases to be modeled explicitly
- Particles modeled as distinct elements

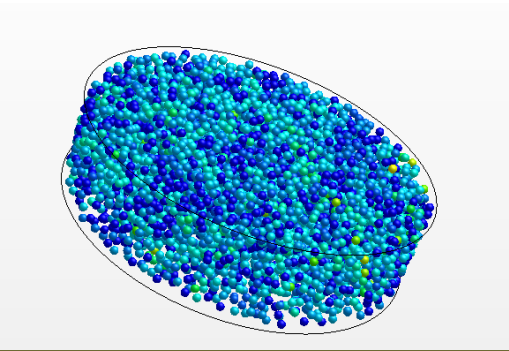
$$m_{particle} \frac{dv}{dt} = F_{drag} + F_{pressure} + F_{body} + F_{contact} + F_{lubrication}$$

- Uses “soft” particles – allow for volume overlap





— No Slip Wall — Atmospheric Pressure



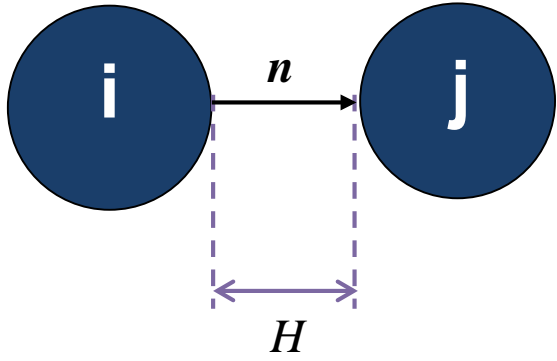
- CFD software with DEM capabilities
- Domain based on rheometer geometry
- Particles and fluid phases coupled through drag and pressure forces

$$S = - \left(\frac{1}{\Delta t} \right) \sum_i \int_0^{\delta t} (\mathbf{F}_{drag} + \dot{m}_i \mathbf{v}) \delta t$$

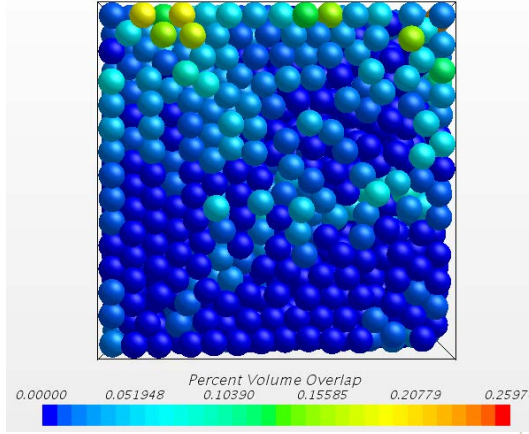
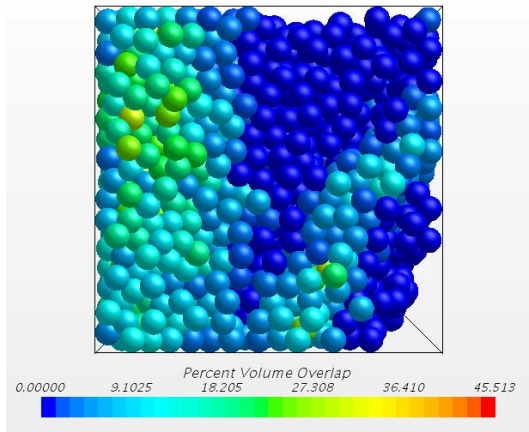


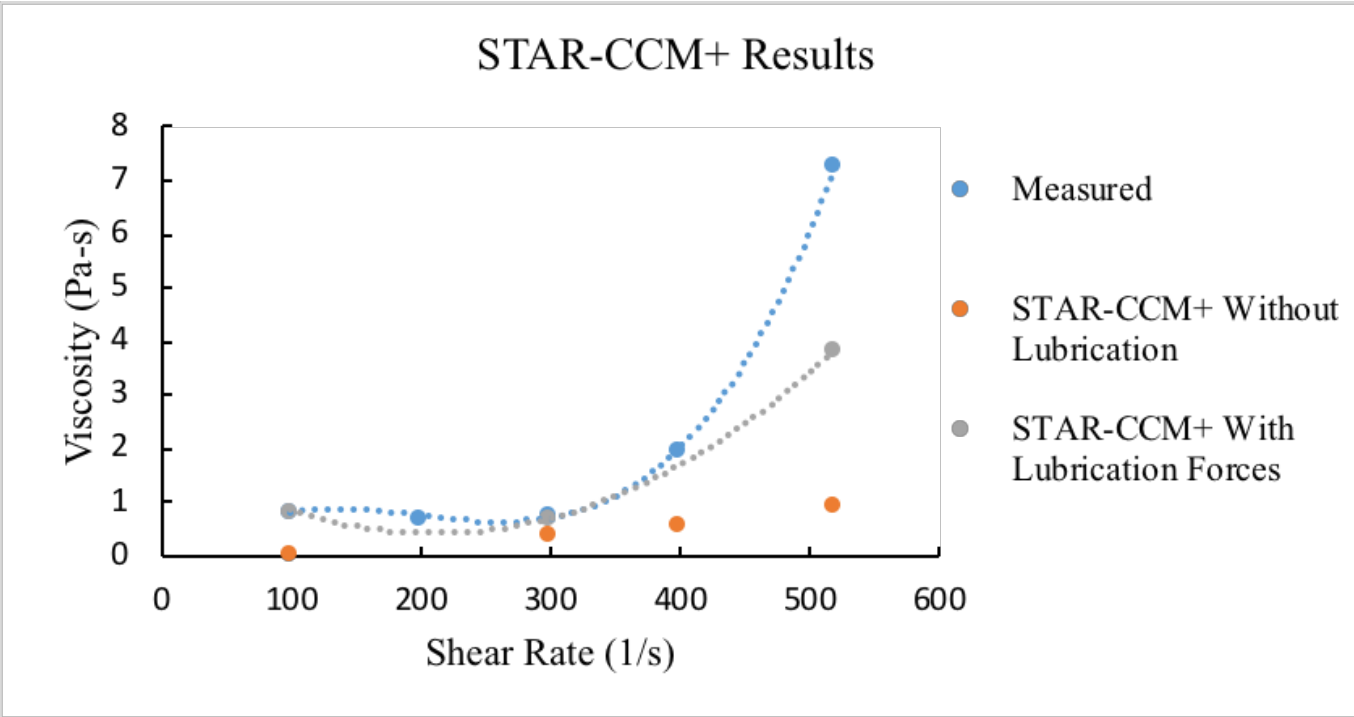


- Lubrication forces necessary for particles to disperse



$$F_v^n = \frac{6\eta_f\pi R^2}{H} \left((v_i + v_j) \cdot n \right) n$$





- $\eta = -1.511 + 0.0344\dot{\gamma} - 0.002(\dot{\gamma})^2 + 3 * 10^{-7}(\dot{\gamma})^3$
- $\eta = 1.992 - 0.0015\dot{\gamma} + 4 * 10^{-5}(\dot{\gamma})^2$





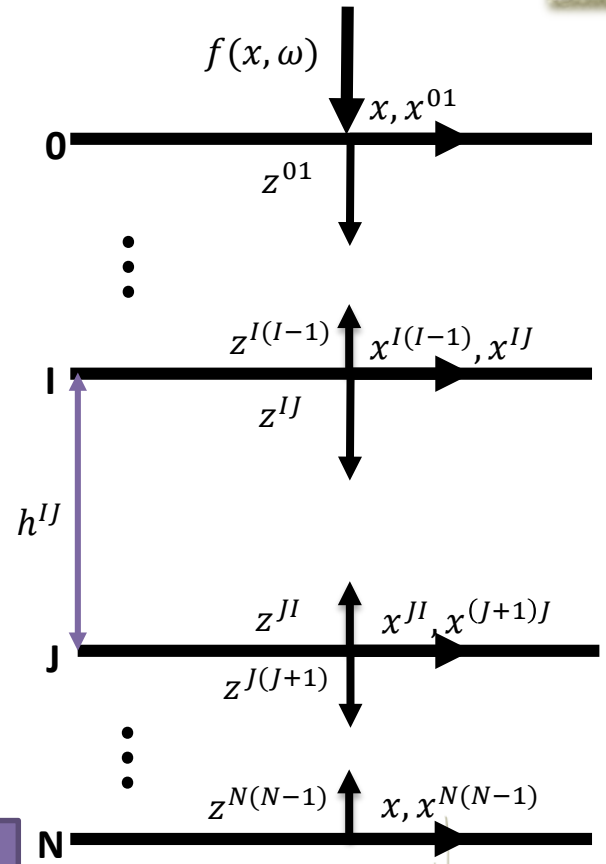
- Used to model multilayer plates
 - Reduced order model
 - Uses plane wave theory
- Double Fourier Transform – allow to analyze in the frequency domain
- Reverberation matrix – R

$$W(k, z, \omega) = (APU + D)[I - R]^{-1} \tilde{x}$$

Response

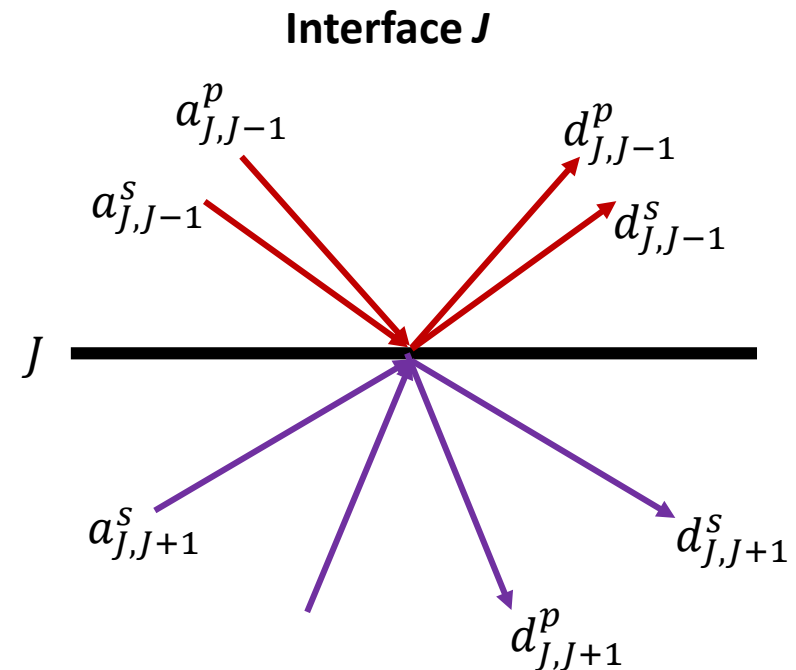
Transfer Function

Input Force



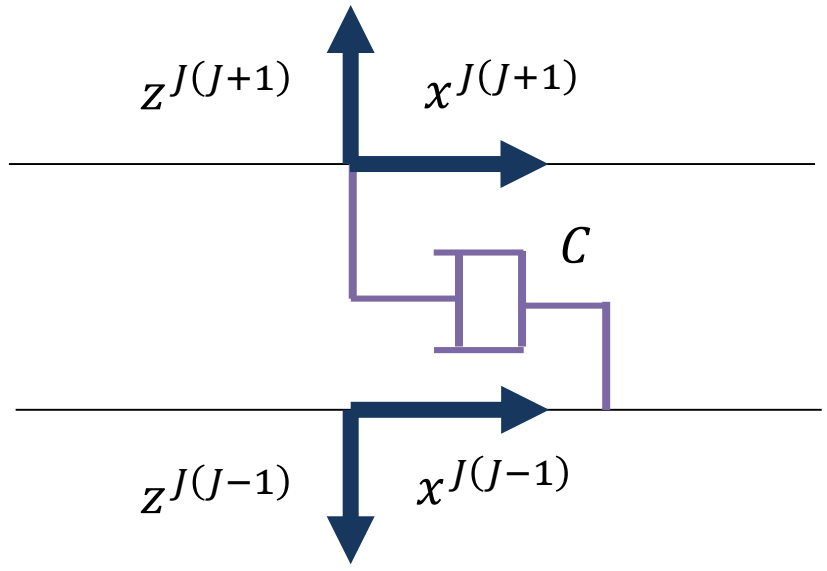


- Reverberation matrix - R
$$R(k, \omega) = S \cdot P \cdot U$$
- Scattering Matrix – S
 - Takes into account boundary conditions
- Phase Matrix – P
$$\begin{pmatrix} e^{j\alpha_J h_J} & 0 \\ 0 & -e^{j\beta_J h_J} \end{pmatrix} = P_J$$
- Permutation Matrix – U
 - Change of coordinates





- Model STF as damper



- Boundary Conditions – With STF

– Equilibrium of Stresses

$$\sigma_{xz}^{J(J-1)} + \sigma_{xz}^{J(J+1)} = 0$$

$$\sigma_{zz}^{J(J-1)} - \sigma_{zy}^{J(J+1)} = 0$$

– Continuity of Vertical Displacement

$$u_z^{J(J-1)} + u_z^{J(J+1)} = 0$$

– Sliding effects

$$\dot{u}_x^{J(J-1)} - \dot{u}_x^{J(J+1)} = \frac{\sigma_{xy}}{C}$$





- Equivalent damping coefficient

- Work done by damper:

$$W = \oint C_{eq} \dot{u}_x dx = \int_0^{\frac{2\pi}{\omega}} C_{eq} \dot{u}_x^2 dt$$

- Work done to shear fluid:

$$W = \oint \tau dx = \oint \eta \dot{\gamma} dx = \int_0^{\frac{2\pi}{\omega}} \eta \frac{\partial \dot{u}_x}{\partial z} \dot{u}_x dt$$

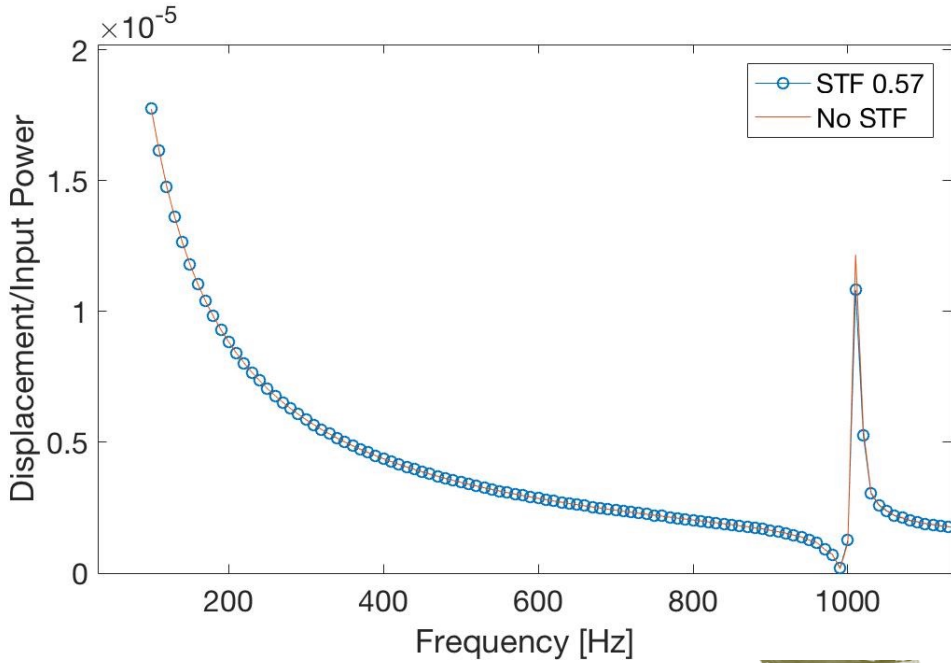
- Set equal:

$$C_{eq} = \frac{\eta}{h}$$





- Multilayer plate of steel - five layers
 - Thin layer of STF along interface
- Implementing STF results in 8% decrease in energy of response





- Microscale simulations indicate the importance of lubrication forces in modeling the shear thickening behavior of STFs
- Macroscale model showed that implementing STFs into multilayer plates reduces their dynamic response.
- STFs may provide a unique energy absorption mechanism for multilayer plates used in vehicle armor.





- Developing an improved model of the particle lubrication forces
- Implementing high pressure loading conditions to the microscale model to study its effect on the model's results
- Experimental validation





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