Materials & Advanced Manufacturing (M&AM)

Modeling of Shear Thickening Fluids for Analysis of Energy Absorption Under Impulse Loading

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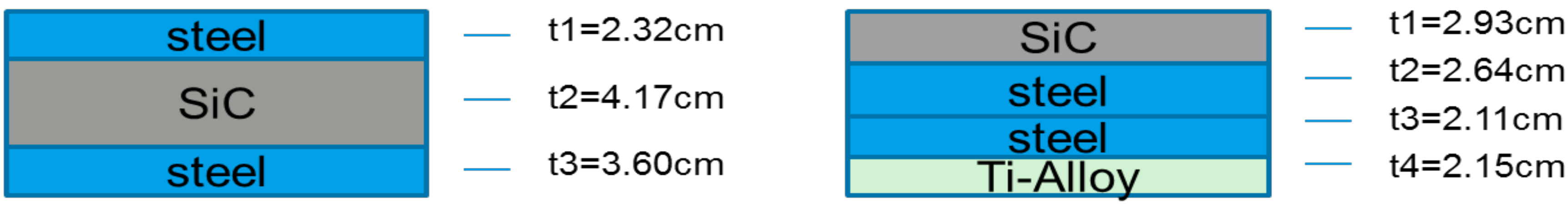
Introduction - Motivation

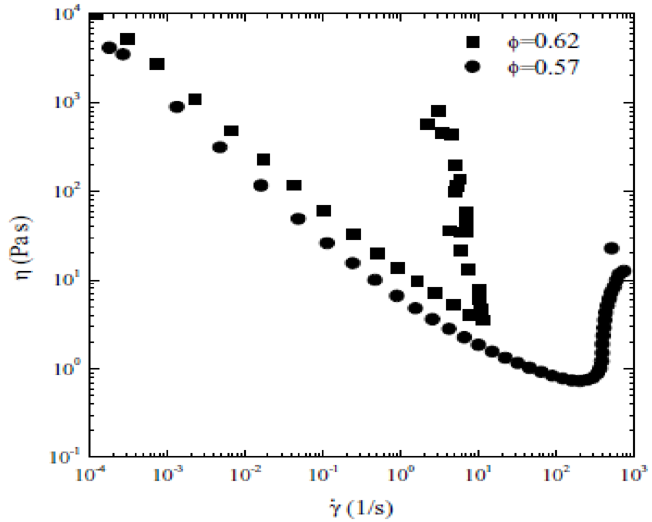
- Developing lightweight structures that provide occupant safety and structural durability is critical for future military vehicles
- Multilayer plates allow for optimization of material properties
- Damping mechanisms between layers should improve shock absorption
  - Shear thickening fluids (STFs)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



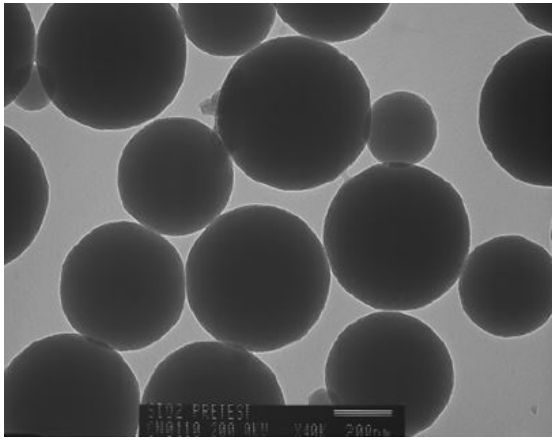
Examples of Multilayer Plates

Introduction - Shear Thickening Fluids

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



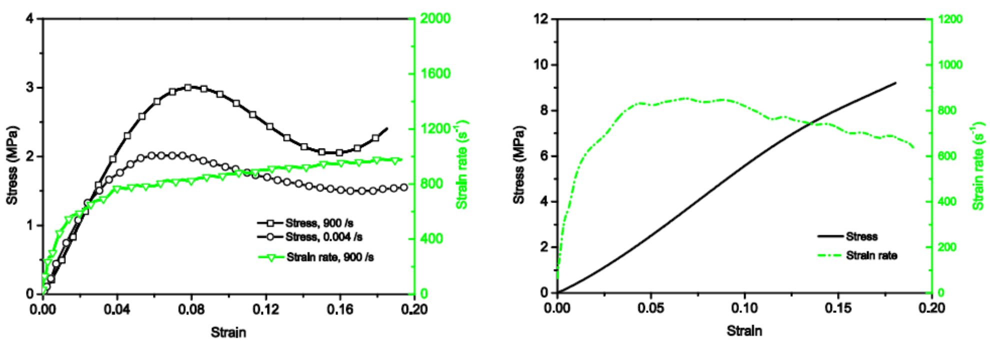
Viscosity v Shear Rate



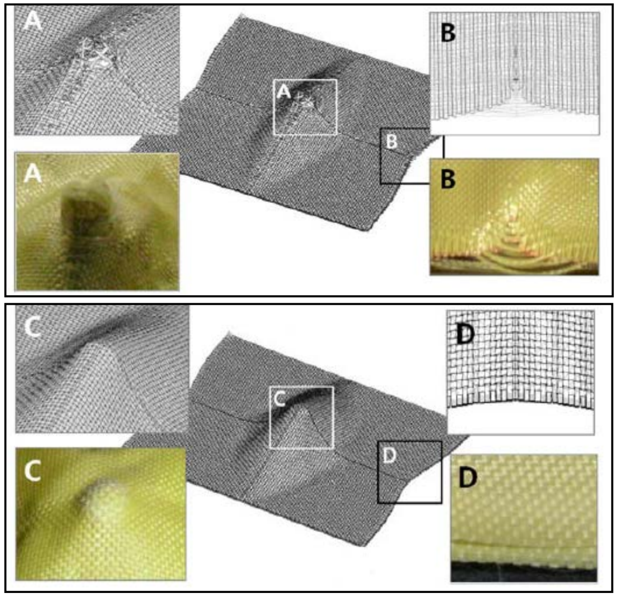
Electron Microscopy of Silica Particles []

Introduction- Shear Thickening Fluids

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



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



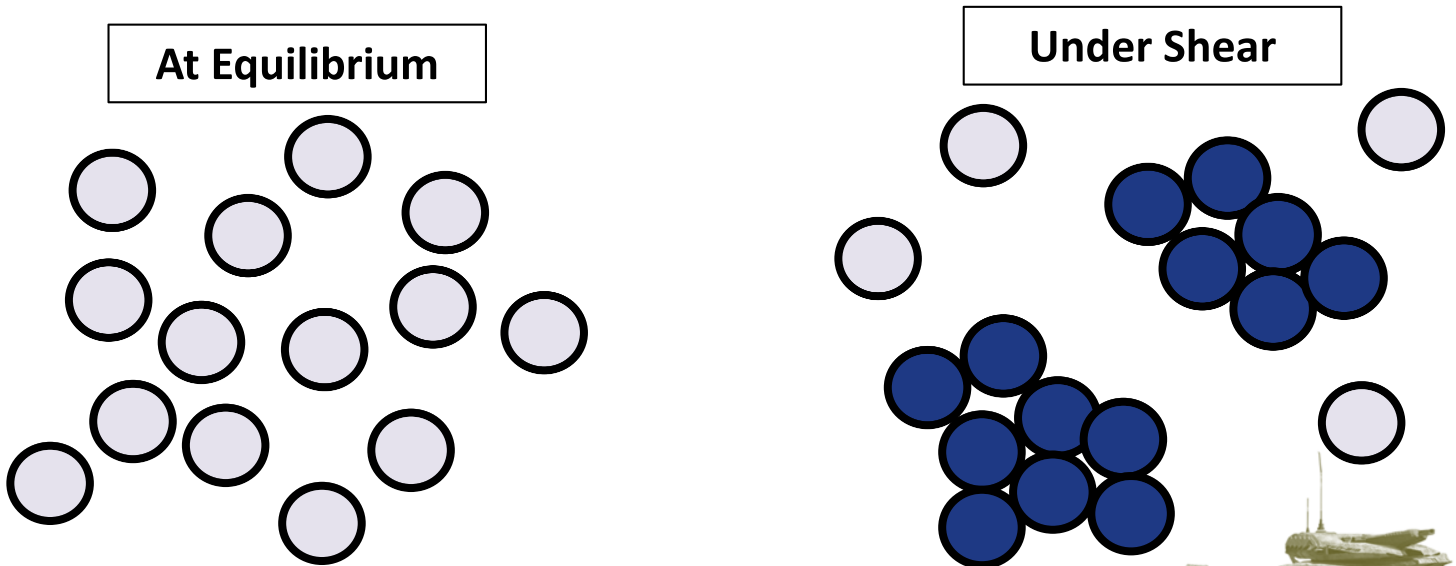
Ballistic Results for Regular and STF Impregnated Kevlar []

Introduction – Objectives

- 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

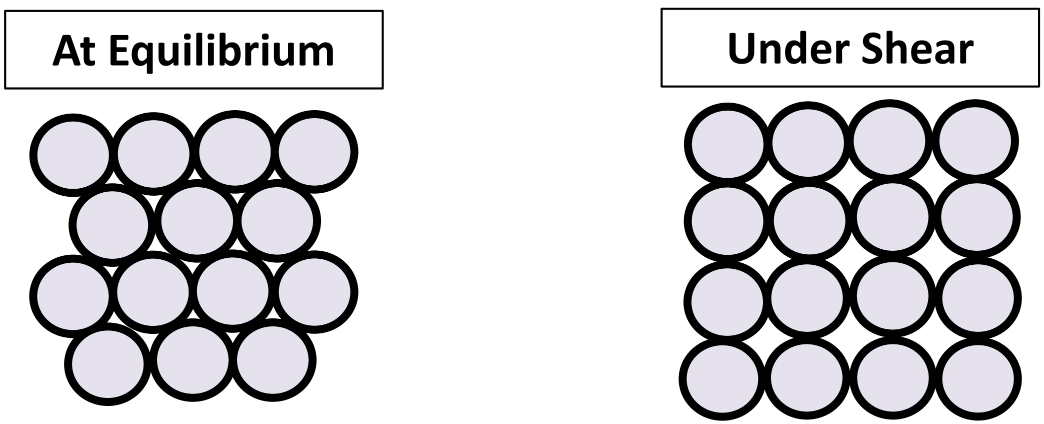
Microscale Model – Shear Thickening Mechanisms

- 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



Microscale Model - Shear Thickening Mechanisms

- 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

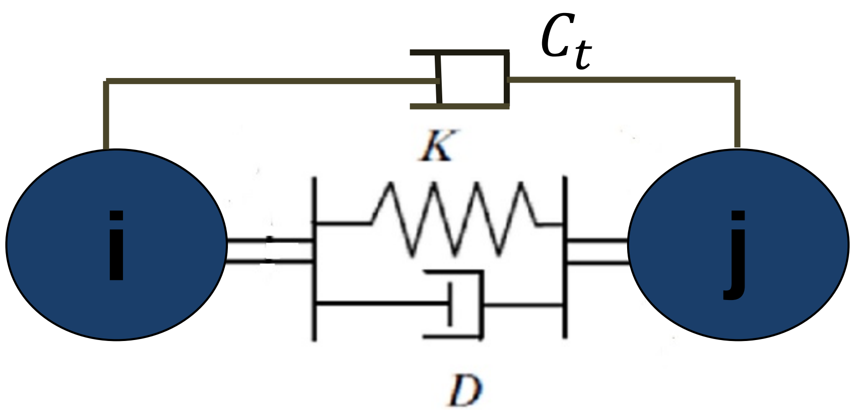


Microscale Model – Discrete Element Method

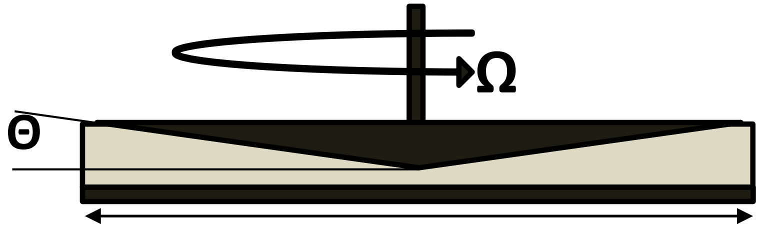
- Meshless, Lagrangian method used to model particles
  - Allows for particles and fluid phases to be modeled explicitly
- Particles modeled as distinct elements

$$m_{particle}\frac{d\boldsymbol{v}}{dt} = \boldsymbol{F}_{drag} + \boldsymbol{F}_{pressure} + \boldsymbol{F}_{body} + \boldsymbol{F}_{contact} + \boldsymbol{F}_{lubrication}$$

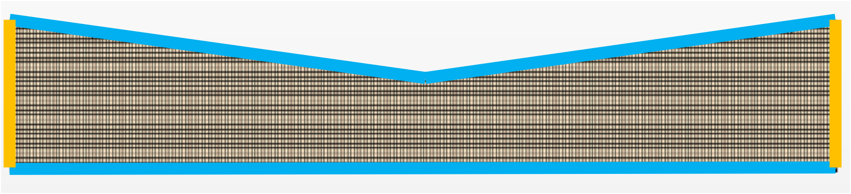
- Uses "soft" particles – allow for volume overlap



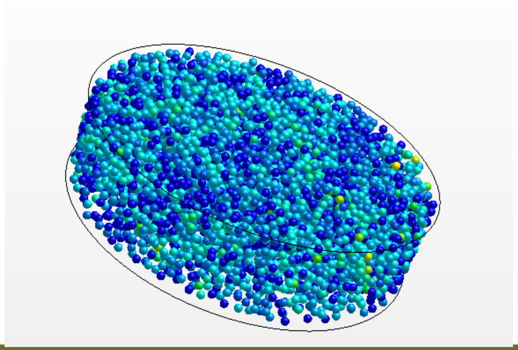
Microscale Model – STAR CCM+



Rheometer Dimensions



No Slip Wall   Atmospheric Pressure

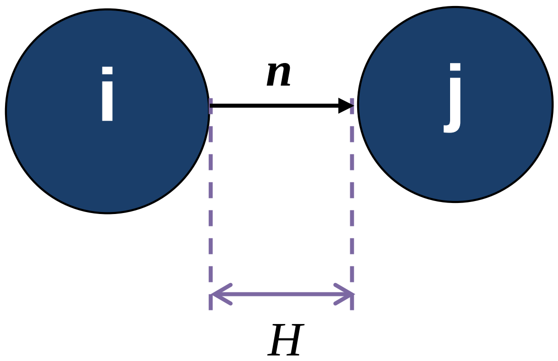


- CFD software with DEM capabilities
- Domain based on rheometer geometry
- Particles and fluid phases coupled through drag and pressure forces

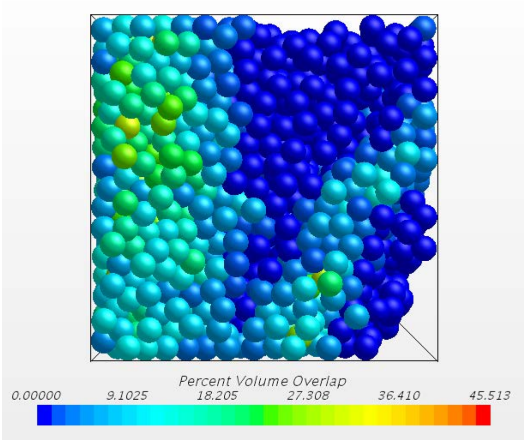
$$S = -\left(\frac{1}{\Delta t}\right)\sum_i \int_0^{\delta t} \left(\boldsymbol{F}_{drag} + \dot{m}_i \boldsymbol{v}\right)\delta t$$

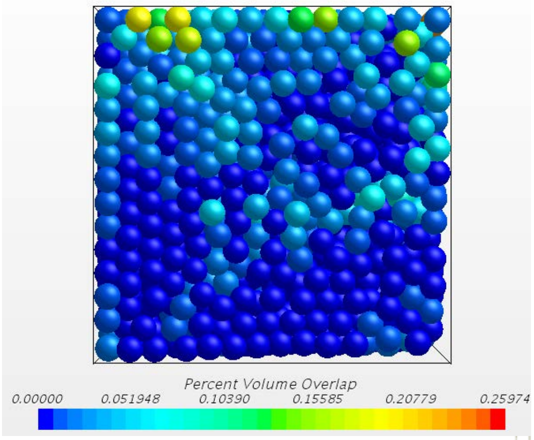
Microscale Model – STAR-CCM+

- Lubrication forces necessary for particles to disperse

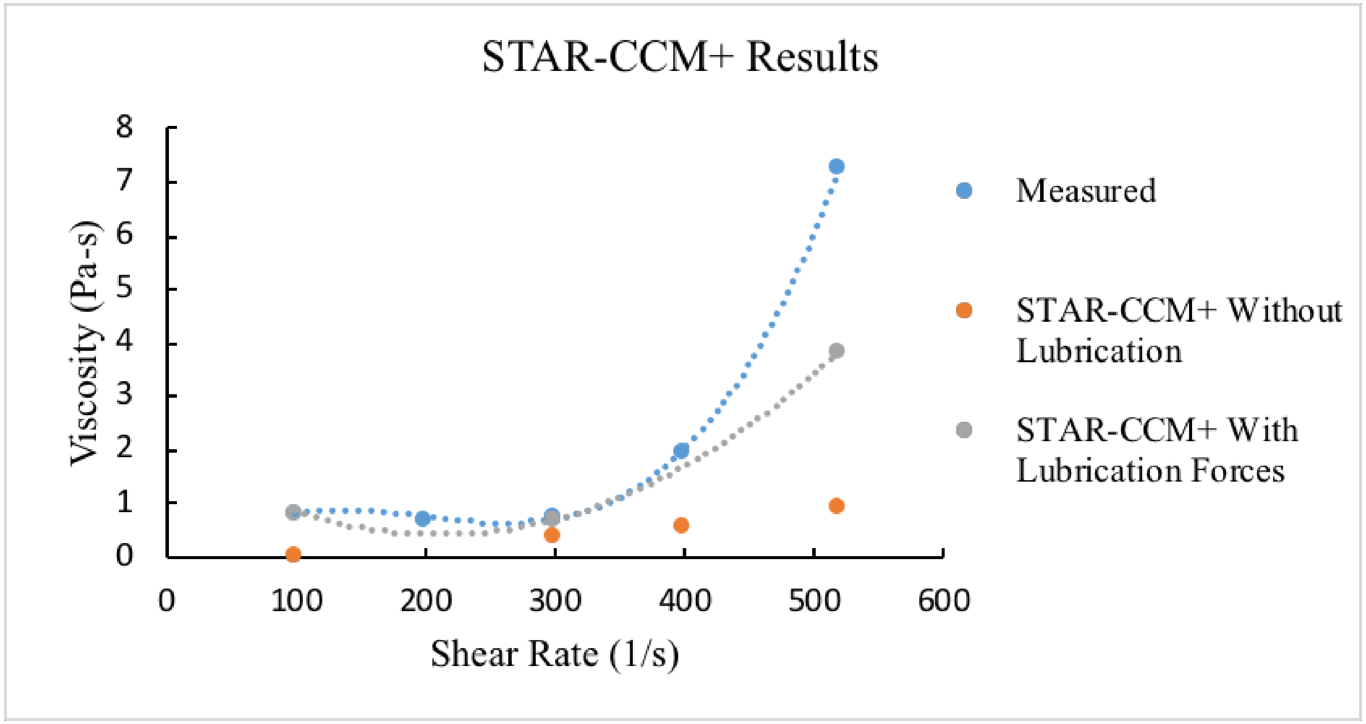


$$\boldsymbol{F}_v^n = \frac{6\eta_f \pi R^2}{H}\left(\left(\boldsymbol{v}_i + \boldsymbol{v}_j\right)\cdot \boldsymbol{n}\right)\boldsymbol{n}$$





Microscale Model – Results



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

Macroscale Model – Reverberation Matrix Method

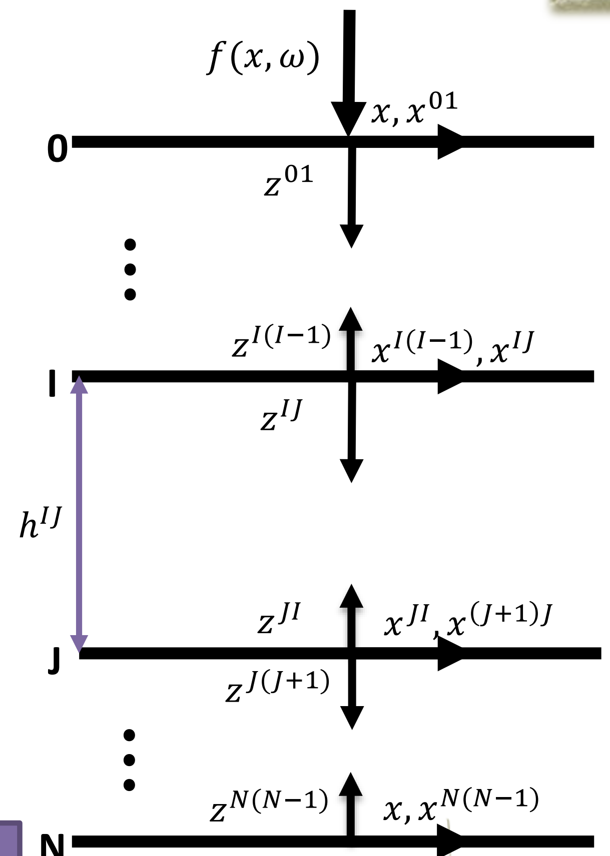
- Used to model multilayer plates
  - Reduced order model
  - Uses plane wave theory
- Double Fourier Transform – allow to analyze in the frequency domain
- Reverberation matrix – R

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

Response: $W(k,z,\omega)$

Transfer Function: $(APU + D)[I - R]^{-1}$

Input Force: $\tilde{s}$



Macroscale Model – Reverberation Matrix Method

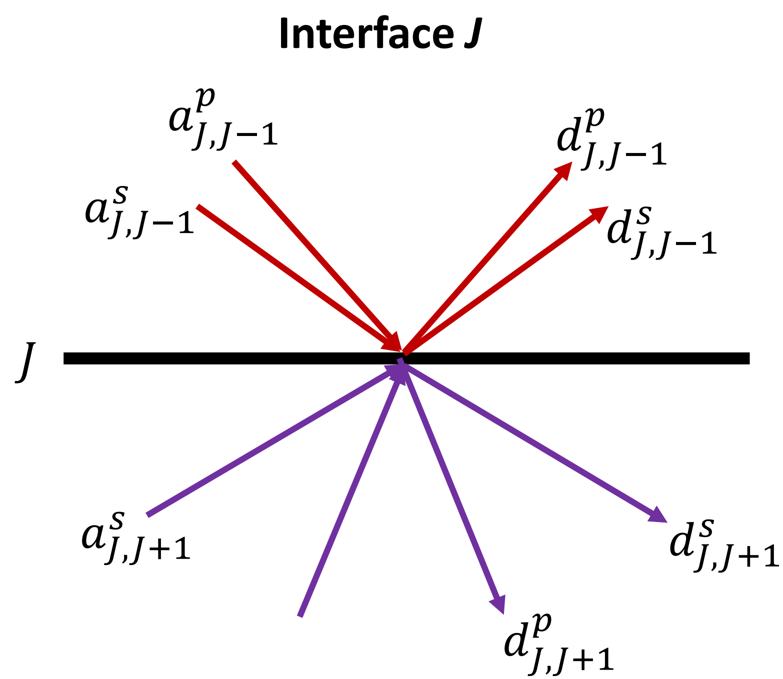
- Reverberation matrix - *R*

$$R(k, \omega) = S \cdot P \cdot U$$

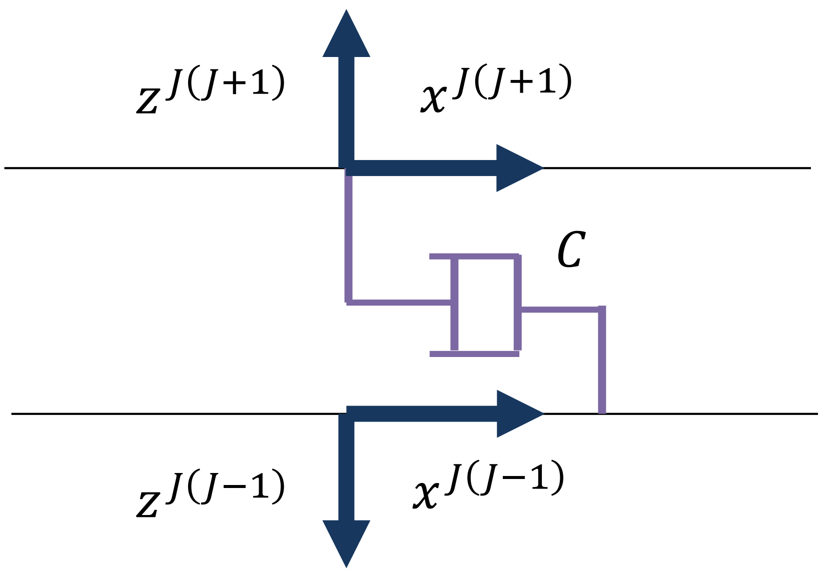
- Scattering Matrix – *S*
  - Takes into account boundary conditions
- Phase Matrix – *P*

$$\begin{pmatrix} e^{j\alpha_J h_J} & 0 \\ 0 & -e^{j\beta_J h_J} \end{pmatrix} = P_J$$

- Permutation Matrix – *U*
  - Change of coordinates



- Model STF as damper



- <u>Boundary Conditions – With STF</u>
  - 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:

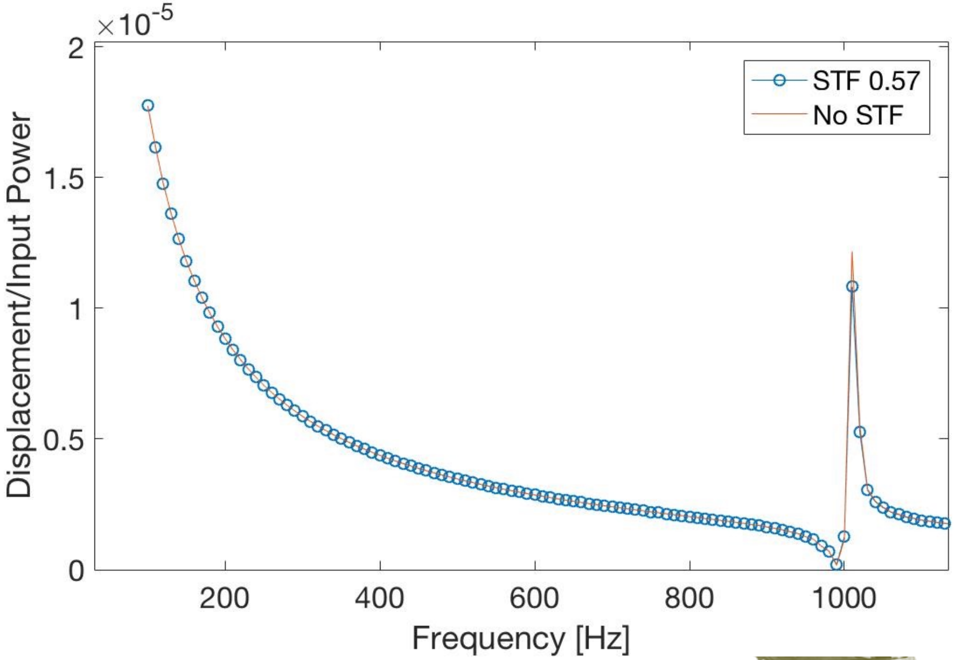
$$W = \oint \tau dx = \oint \eta\dot{\gamma} dx = \int_0^{\frac{2\pi}{\omega}} \eta \frac{\partial \dot{u}_x}{\partial z}\dot{u}_x dt$$

  - Set equal:

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

Macroscale Model – Results

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



Conclusions

- 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.

Future Work

- 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

References

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Acknowledgment and Disclaimer

This work was supported in part the Automotive Research Center, a US Army Center of Excellence for modeling and simulation of ground vehicles

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