

Modeling solid-solid contact in a fully Eulerian phase-field framework

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Modeling solid-solid contact in a fully Eulerian phase-field framework

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Motivation - solid *growth/evolution* in constrained space

3. Zhang et al., PNAS, 2021



Multiphysical processes lead to interfacial interactions •

Why *Eulerian* framework?



• Multiphysical processes are better described in Eulerian framework

How to model *contact* in Eulerian framework?



Key ingredients to contact in Eulerian framework



How to *track solids* in Eulerian framework?



• Phase-field approach along with Cahn-Hilliard advective evolution

How to describe *elasticity* in Eulerian framework?



Mapping current to reference configuration $\xi(\boldsymbol{x},t) \rightarrow \boldsymbol{X}$ $\frac{\partial \xi}{\partial t} + \frac{\partial \boldsymbol{u}}{\partial t} \cdot \nabla \xi = \boldsymbol{0}$

Constructing deformation gradient

$$\boldsymbol{F}(\boldsymbol{x},t) = \frac{\partial \boldsymbol{x}}{\partial \boldsymbol{X}} = \left(\frac{\partial \boldsymbol{X}}{\partial \boldsymbol{x}}\right)^{-1} = (\nabla \boldsymbol{\xi}(\boldsymbol{x},t))^{-1}$$

Using constitutive laws

$$\boldsymbol{\sigma} = f(\boldsymbol{F})$$

Kamrin et al., JMPS, 2012
 Rycroft et al., Journal of Fluid Mechanics, 2020

How to *detect contact* in Eulerian framework?



• Contact detection becomes trivial and contact force as volumetric forces

Coupling all the ingredients

Solving for the elasticity

$$\sum_{i=1}^{2} \nabla .(\phi_i \boldsymbol{\sigma}(\boldsymbol{\xi_i})) + \boldsymbol{b_i} = 0$$

Advect phasefields according to displacements

$$\frac{\partial \phi}{\partial t} + \frac{\partial \boldsymbol{u}}{\partial t} \cdot \nabla \phi = -\nabla \cdot \mathcal{M} \nabla \mu$$
$$\mu = \frac{\delta \mathcal{E}_{\text{pf}}}{\delta \phi}$$

Updating the reference map

$$\frac{\partial \xi}{\partial t} + \frac{\partial \boldsymbol{u}}{\partial t} \cdot \nabla \xi = \boldsymbol{0}$$

System of equations for a single body

$$\underbrace{\begin{bmatrix} \mathbf{K}_{\boldsymbol{u}} & \mathbf{K}_{\boldsymbol{u}\boldsymbol{\xi}} & \mathbf{K}_{\boldsymbol{u}\boldsymbol{\phi}} & 0 \\ & \mathbf{K}_{\boldsymbol{\xi}} & 0 & 0 \\ & & \mathbf{K}_{\boldsymbol{\phi}} & \mathbf{K}_{\boldsymbol{\phi}\mu} \\ & & & \mathbf{K}_{\boldsymbol{\mu}} \end{bmatrix}}_{\mathbf{K}^{k}} \cdot \underbrace{\begin{bmatrix} \boldsymbol{u} \\ \boldsymbol{\xi} \\ \boldsymbol{\phi} \\ \boldsymbol{\mu} \end{bmatrix}}_{\mathbf{u}^{k}} - \underbrace{\begin{bmatrix} \boldsymbol{b}(\boldsymbol{\phi}) \\ \mathbf{0} \\ 0 \\ 0 \end{bmatrix}}_{\mathbf{f}^{k}} = \mathbf{0}$$

Coupled system for two bodies $\begin{bmatrix} [\mathbf{K}^k] & \mathbf{0} \\ & [\mathbf{K}^l] \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u}^k \\ \mathbf{u}^l \end{bmatrix} - \begin{bmatrix} \mathbf{f}^k \\ \mathbf{f}^l \end{bmatrix} = \mathbf{0}$

1. Lorez et al., Eulerian framework for contact between solids represented as phase fields, CMAME, 2024

Does the method *work*?



Hertz contact



Contact force field (before)

Contact force field (after)

Hertz contact



Effect of interface region

Contact area

How *robust* is the method?



Can handle *large deformations*



Can handle *large deformations*



Can handle *evolving surfaces*



Can handle *evolving surfaces*



Evolution of Von-Mises stress

Can handle *complex domains*





Rough-on-Rough contact

Can handle *friction*



Tangential slip
$$oldsymbol{u_t^{ij}} = oldsymbol{P} \cdot (\Delta oldsymbol{u_i} - \Delta oldsymbol{u_j})$$

Tangential force $\boldsymbol{b_t} = \lambda \cdot \mu \boldsymbol{b_n} \cdot \frac{\boldsymbol{u_t}}{\|\boldsymbol{u_t}\|}, \quad \lambda \in [0, 1]$

Balance of linear momentum

$$\nabla \cdot (\phi_i \boldsymbol{\sigma}(\boldsymbol{\xi}_i)) - \boldsymbol{b}_n^i - \boldsymbol{b}_t^i = \boldsymbol{0}$$

Can handle *friction*



Cattaneo-Mindlin Traction Profile



Conclusion

- A <u>robust methodology</u> to handle <u>interfacial interactions</u> within <u>Eulerian</u> framework.
- Allows *strong coupling* of multiphysical process with contact.
- <u>Contact detection</u> phase becomes <u>trivial</u>.
- Can handle *large deformation*, *complex surfaces* and *friction*.



Thank you for your attention.

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Lorez et al., Eulerian framework for contact between solids represented as phase fields, **CMAME**, 2024

