Advances in STAR-CCM+ DEM models for simulating deformation, breakage, and flow of solids

Satish Bonthu
Overview of DEM in STAR-CCM+

Recent DEM improvements
- Parallel Bonds in STAR-CCM+
- Constant Rate Damage Model
- Maximum Packing Random Injector
- Particle Depletion Model
- Abrasive Wear Model

Simulation studies
- Compression of brittle material
- Rock drilling
- Erosion in a pipe bend
- Erosion due to water jet

Summary
DEM is used to model particles of different sizes and shapes.

- DEM resolves the collisions between particles.
- Particles can be bonded together to form deformable / breakable material.
DEM Governing Equations

- **Momentum conservation**
  \[
  m_i \frac{dv_i}{dt} = \sum_j F_{ij} + F_g + F_{fluid}
  \]
  
  where \(m_i\) and \(v_i\) are mass and velocity of particle \(i\), \(F_g = m_i g\) is gravity force, \(F_{ij}\) is contact force between particle \(i\) and element \(j\).
  - DEM is a meshless method
  - DEM is computationally intensive method

- **Conservation of angular momentum**
  \[
  \frac{d}{dt} I_i \omega_i = \sum_j T_{ij}
  \]
  
  where \(I_i\) and \(\omega_i\) are the momentum on inertia and rotational velocity of particle \(i\).
  \(T_{ij} = r_{ij}(F_{ij} + F_r)\) is the torque produced at the point of contact and it is the function of the rolling friction force \(F_r\).
Contact forces

Particle A

Particle B

Normal component of contact force

Tangential component of contact force

Normal restitution

Tangential restitution

Friction

Young’s modulus (stiffness)
# Contact models in STAR-CCM+

## Basic models

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hertz-Mindlin</td>
<td>Classical nonlinear contact force model for rigid bodies</td>
</tr>
<tr>
<td>Walton-Braun</td>
<td>Linear model for deformable particles</td>
</tr>
<tr>
<td>Linear Spring</td>
<td>Linear model for rigid bodies</td>
</tr>
</tbody>
</table>

## Optional models

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling Resistance</td>
<td>Three models for resisting rolling</td>
</tr>
<tr>
<td>Linear Cohesion</td>
<td>Constant attractive force</td>
</tr>
<tr>
<td>Artificial Viscosity</td>
<td>Velocity dependent damping model</td>
</tr>
<tr>
<td>Heat Conduction</td>
<td>Heat flow through contact</td>
</tr>
<tr>
<td><strong>Parallel Bonds</strong></td>
<td>Bonds resisting to tension, bending, twist</td>
</tr>
</tbody>
</table>
Two STAR-CCM+ models use same bond physics

- Parallel bond contact model
  - Bonds are formed after injection at each new contact
  - User specifies time interval of bonding
- Bonded particle model
  - Used to create clumped particles:
  - Bonds are formed at the moment of injection

Recent improvements
- Bond strength distribution, visualization, and...
Bond Failure Models in STAR-CCM+

Simple Failure Model

Constant Rate Damage Model
New in version 10.04
$k_r$ is the fracture softening modulus, model parameter
Example of Brazilian compression test

- Standard test to determine the strength of brittle material
- Solid material is modeled as particles bonded together
Sample preparation

New Maximum Packing option in Random Injector

- Particles “grow from seeds” until whole region is fully packed
- Resulting configuration has no overlaps between particles

200 seeds

10000 seeds
Geometry involves stationary bottom wall and moving down top platen

- Particles are injected using table injector with “Allow overlap” option
  - Particle diameters are “inflated” by factor 1.01 to ensure small overlaps
- Bonds are set to form for first 0.1 s before starting compression
Animation of compression test

Solution Time 0.001 (s)  Ram Displacement: 5e-06
Both “Simple Failure” and “Constant Rate Damage” models were tested:

- Only “Constant Rate Damage” model reproduced the vertical crack observed in experiment

Bonds model parameters (Normal and Tangential strength of bonds, its distribution) were calibrated to reproduce the target material

- Soft sandstone in our tests
Example of rock drilling

- Rock is permeable with void fraction =0.4
- Overset mesh is used to rotate and advance the drill-bit down
- Solution for drilling fluid flow was obtained using 2-way coupling model
- Jet flow form nozzles results in large drag forces on bonded grains (jetted erosion)
Erosion and Wear in Solids Processing Equipment

Slurry flow in pipes
erosion

Drilling rock

Sediment flow, Gravel Packing
New in version 10.04
Relevant for flow regimes
  - With high solids loading
  - Prolonged “sliding” contact between particles and geometry
Abbrad Model:

\[ M_e = C \sum_{\text{contacts}} \int F_n v_{ct} dt \] is mass eroded from single surface cell
- \( C \) is abrasive wear coefficient in units of kg/J (model parameter)
- \( F_n \) is normal component of particle-cell contact force
- \( v_{ct} \) is tangential component of particle-cell relative velocity at the point of contact
- \( dt \) is DEM timestep

Field Function option:

\[ M_e = C \sum_{\text{contacts}} \int F(c) dt \]
- \( F(c) \) is user field function

At the end of each timestep, for each surface cell,
- Erosion rate calculated as

\[ E_r = \frac{1}{T} \frac{1}{A_{cell}} M_e \]
  - \( T \) is the timestep
  - \( A_{cell} \) is the area of surface cell
- \( M_e \) is reset to zero
- \( E_r \) is available for postprocessing
Model properly accounts for

- All contacts during timestep
- Variation of contact force strength and relative velocity for single particle during prolonged “sliding contact”

Abrasive wear coefficient is often related to “hardness” of boundary

Best for flows when harder particles are sliding along softer boundary

Abrasive wear model is compatible with coarse grain model
Elbow pipe example, top view

Inlet

Mean Parcel Diameter = 10 mm
Mesh size 20 mm

Outlet

2 m

0.4 m

1 m
Random injector
- Uses “Maximum Independent Set” Algorithm to provide High Solid Loading flow
- Fast, mesh independent
- Initial particle velocity:
  - Horizontal component = inlet fluid velocity
  - Small “down component”
Initial Results for Elbow flow
Segment of pipe (or solids buildup inside pipe) can be modeled using DEM particles bonded together
- $D_{\text{inner}} = 0.3 \text{ m}$
- $D_{\text{outer}} = 0.4 \text{ m}$

Water flow is set with inlet at one end of DEM pipe and outlet at another end

Inlet velocity is tilted 10 deg with respect to inlet normal
- One side of pipe should experience more erosion
Initial Results with Constant Rate Damage Model

- Inlet velocity in aggressively ramped from 0 till 20 m/s over simulated time
- Fully 2-way coupling between DEM and CFD
DEM Post-processing

Particles: 36186

Solution Time 1.70001 (s)
Features used to create bonded assembly

- **Maximum packing option in random injector**
  - Allows obtaining tight packing of particles without timestepping
  - For size distribution, smaller particles are injected after larger ones are in the system

- **Particle depletion model**
  - New in version 10.04
  - Allows removing subset of particles (clean central core area)

- **Table injector**
  - Allows loading the saved particle assembly with “inflated diameters”
Summary

- Improved parallel bonds
- New injection and depletion options
- Improved accuracy in modeling brittle materials processing
- New abrasive wear model
- Accurate prediction of equipment damage
Back-up slides
Constant rate damage model references

