Critical trade-offs when using Explicit Dynamics

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Outline

• Introduction to Explicit Dynamics
• Space Related Simulation Examples
• The Best Approach to Explicit Dynamics
• Looking Into the Future
Main Engineering Simulation Tools

- CFD
- Explicit Structural
- Implicit Structural
Problems Well Suited for Explicit Solutions

- Short duration localized phenomena
- Transient dynamic wave propagation
  - Gases, Liquids, Solids and their Interaction (FSI)
- Nonlinear
  - Material behavior
  - Structural behavior
  - Contact/Interaction
- Extreme loadings
  - Extreme deformations
    - Large strains & strain rates
  - Material failure
  - Fragmentation
History of Explicit Dynamics

• Initial development of Explicit Solutions
  – At US National Laboratories 1960 - 1980
  – Extensive investment by US Government
  – Solutions 1D & 2D, simple models, crude meshing
  – Supercomputers used
  – Time consuming, labor intensive problem setup
• Today’s state of Explicit Solutions
  – Fully integrated CAD to solution
  – Automatic meshing, material libraries
  – Easy to use GUI
  – HPC solution removes problem size limitations
• Future:
  – Simulation that speaks an engineers language
  – Modern user environment via cloud
Outline of calculations in one time step

Direct Calculation

Nodal Velocities & Displacements

Integration

Nodal Accelerations

Force/Mass

Material Model

Zone Volumes & Strain Rates

Conservation of Momentum

Zone Pressures & Stresses

Nodal forces

Boundary and/or Interactive Forces
Time Step – the heartbeat of explicit

- Time step used in Explicit time integration is limited by the CFL (Courant-Friedrichs-Levy) condition.
- Stress waves must not travel further than the smallest element dimension in the mesh, in a single time step.
- The time steps used for explicit time integration will generally be much smaller than those used for implicit time integration.
- Example:
  - characteristic dimension of 1 mm
  - sound speed of 5000 m/s (like iron)
  - stability time step 0.18 µ-seconds
  - problem time of 0.1 seconds
  - will require 555,556 time steps

\[ \Delta t \leq f \left( \frac{h}{c} \right) \]

\[ h \]

\[ \min \]
Mesh Distortion and erosion

Simple impact

Distorted elements

Eroded elements

Internal energy lost
Inertia retained
Explicit Solution Methods

Lagrange (structures)

Euler (fluids)

ALE (auto remesh)

SPH (hypervelocity & brittle)
Explicit Model Set-Up Trade-Offs

Accuracy

Ease of Use

Computer Time

Critical trade-offs when using Explicit Dynamics
Space related simulation examples

1. Hypervelocity impact
2. Planetary impact
3. Aircraft impact
4. Bird strike
5. Blade-out
6. Fragment and blast loading
7. HYDRAM
8. Splashdown
Critical trade-offs when using Explicit Dynamics
Hypervelocity Impact on Honeycomb
Critical trade-offs when using Explicit Dynamics

Planetary Impact

Planetary Impacts
Understanding the evolution of planetary geology

Micro Meteoroid Impacts

20km Projectile

20km/s Impact on Geological Material

1μm Particle

Solid
Liquid
Vapour

Initial Crater Formation

Courtesy, Emily Baldwin, University College London
Airplane Impact on Reinforced Concrete

Critical trade-offs when using Explicit Dynamics
Airplane Impact on Structure

Critical trade-offs when using Explicit Dynamics
Bird Strike on a Wing
Bird Strike on Nose of an Airplane

Animation of impact on nose
Bird Strike on the Wing of an Airplane
Turbine Fan Blade-out
Blast and Fragment Loading

Carbon Fiber Reinforced (CFRP) wing
Rocket Propelled Grenade (RPG) weapon
Air Blast modeled using the Euler Blast solver
RPG casing (fragments) and wing box components modeled using Lagrange solvers
Euler-Lagrange coupling used for the blast loading
Lagrange contact and erosion used for the fragment loading
Bullet Impact Into Fuel Tank (HYDRAM)

Impact of a 12.7 mm round at 1044 m/s on an aluminum fuel tank

Material Location  Pressure Contour
Belly Landing of the LocalHawk UAV
Failure of composite skin from landing
Master’s thesis by Hans Magnus Thorsen
Chalmers University Of Technology Sweden
Simulation of Capsule Splashdown

http://youtu.be/GM7bIYHIMtY
The Best Approach to Explicit Dynamics

- Use simple material models
- Start with a simple problem (Use 2D if possible)
- Simplify geometry
- Create uniform hex mesh if possible
- Select appropriate solution methods (Material response based)
- Cheat if necessary (Erosion and mass scaling)
- Look at results after a few hundred cycles
- Correlate with experiment or publication
- Use HPC (parallel processing) to reduce run times
- Add complexity one step at a time
- Seek insight not numbers
Material Modeling

Materials have a complex response to dynamic loading

The following phenomena may need to be modelled

• Non-linear pressure response
• Strain and strain rate hardening
• Thermal softening
• Directional material properties (composites etc.)
• Damage due to crushing (ceramics, glasses etc.)
• Tensile failure

No single material model can incorporate all of these effects

Use different models, based on the problem model
Material Modeling Implementation

Material modeling method

**EOS:**
1) Calculate Pressure

**Strength:**
2) Calculate Trial Elastic Deviatoric Stresses
3) Compare to Yield Surface
   - Scale back to yield surface if exceeded
   - Update Effective plastic strain

**Failure:**
4. Evaluate Failure Model
### Material Models

**EOS**
- Linear
- Polynomial
- Shock
- Tillotson
- Puff
- SESAME
- Two Phase
- Ideal Gas
- JW
- Lee-Tarver
- Powder Burn(Beta)
- Porous
- Compaction
- P alpha
- Ortho
- Rigid
- Hyperelastic
- User #1

**Strength**
- None
- Elastic
- Viscoelastic
- von Mises
- Johnson Cook
- Piecwise JC
- Zerilli Armstrong
- Steinberg Guinan
- Cowper Symonds
- Drucker-Prager
- MO Granular
- Johnson-Holmquist
- RHT Concrete
- Beam-Resistance
- Orthotropic Yield
- Crushable Foam (Iso)
- Hyperelastic
- Bilinear Hardening
- Multilinear Hardening
- User Strength #1

**Failure**
- None
- Hydro (Pmin)
- Plastic Strain
- Principal Stress
- Principal Strain
- Principal Stress/Strain
- Material Stress
- Material Strain
- Material Stress/Strain
- Cumulative Damage
- Johnson Holmquist
- RHT Concrete
- Tsai/Hoffman/Hill
- Grady Spall Model
- Johnson Cook
- Orthotropic Softening
- MO Granular
- User failure #1

**EOS, Strength and Failure models can be independent**
How to choose material models

- It is relatively easy to identify the basic category that a material lies in
  - Liquid or Solid?
  - Isotropic or Anisotropic/Orthotropic ?
  - Inert or Reactive?
  - Porous or Not ?
  - Ductile or Brittle ?
  - Pressure Dependant Strength (cohesive) or not ?
- The actual set of models used however are highly dependant on the application and the available material data
- **Start with simple models** and progress, as required, to more complex models
  - Lets you understand how parameters influence response and which parameters are critical for good results
Start with a simple model (2D if possible)

Copper jacket bullet penetration into mild steel at 842 m/s

Courtesy Sandia National Laboratory
Simplify Geometry

Defeaturing removes small, unimportant features and reduces element count.
Meshing: Size Matters a Lot

- To resolve peak pressures accurately, the element size must be small relative to the wave frequency
- Impulses are often computed accurately, even if peak pressures are low
- Practical limits on the total number of elements often determines the element size

Element size = 0.003
Number of elements = 1,730
ELAPSED RUN TIME = 0.111 min
Time step = 1.247E-07s

Element size = 0.0015 (0.5X)
Number of elements = 14,175 (8.2X)
ELAPSED RUN TIME = 5.835 min (53.0X)
Time step = 6.295E-09s (0.0198X)
Meshing: Create Uniform Hex Mesh

- **Mid-Surface** thin solids and use shells
## Meshing: Run Time of Solid and Shell Parts

<table>
<thead>
<tr>
<th>Method</th>
<th>Nodes</th>
<th>Elements</th>
<th>Time Step</th>
<th>Run Time (min)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid (all tets)</td>
<td>28,785</td>
<td>139,414</td>
<td>1.063E-8</td>
<td>10.517</td>
<td>16.3</td>
</tr>
<tr>
<td>Mid-Surfaced Bonded</td>
<td>4,137</td>
<td>3,768</td>
<td>1.056E-8</td>
<td>0.805</td>
<td>1.25</td>
</tr>
<tr>
<td>Mid-Surfaced Single Part</td>
<td>4,251</td>
<td>4,040</td>
<td>1.397E-8</td>
<td>0.643</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Element Size: 0.66 mm for all meshes
Assign the Best Solution to Each Part

Lagrange (structures)

Euler (fluids)

ALE (auto remesh)

SPH (hypervelocity & brittle)
Stability Time Step and Mass Scaling

The maximum time step is inversely proportional to the sound speed of the material and directionally proportional to the square root of the mass of material in an element.

\[ \Delta t \propto \frac{1}{c} = \frac{1}{\sqrt{C_{ii} / \rho}} = \sqrt{\frac{m}{VC_{ii}}} \]

where \( C_{ij} \) is the material stiffness \( (i=1,2,3) \), \( \rho \) is the material density, \( m \) is the material mass and \( V \) is the element volume.

Increasing the mass of an element can increase the time step.

If a model contains a few small elements, mass scaling can be used to reduce run time.

Mass scaling does change the inertial properties of the scaled elements.
Mass Scaling Example

Standard Timestep 2.0e-5

Mass scaled timestep 1.0e-4

5x Increase in DT

0.02% Increase in mass

golf_sand_ng_ero
Cycle 0
Time 0.000E+000 ms
Units mm, mg, m³
Correlation: Bullet Penetration

Bullet Penetration of Mild Steel
(338 Winchester Magnum)

a. AUTODYN Simulation

b. Shot 9 Cross-Section

Courtesy Sandia National Laboratory
Correlation: Impact on Ceramic
Correlation: Constrained explosive pressure profile

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Peak Overpressure (kPa)</th>
<th>Peak Impulse (kPa ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Shot 1</td>
<td>1898</td>
<td>982.4</td>
</tr>
<tr>
<td>Shot 2</td>
<td>3341</td>
<td>613.6</td>
</tr>
<tr>
<td>Shot 3</td>
<td>1606</td>
<td>591.2</td>
</tr>
<tr>
<td>Average</td>
<td>2282</td>
<td>729.1</td>
</tr>
<tr>
<td>AUTODYN-3D</td>
<td>2567</td>
<td>708.9</td>
</tr>
</tbody>
</table>
Correlation: Explosively driven bolt cutter
Explicit Dynamics Is Efficient with HPC

Model Courtesy of IBM
440,000 elements

Parallel Speed-up Using MPP

Hardware:
Dual Xeon E5-2690 2.9GHz, 16 cores
Looking Into the Future

How can we improve explicit dynamic tools?

• Encapsulate experience and knowledge
• Remove “numerics”
• Use physics terminology
• Use modern user interfaces
  – Convenient access to cloud computing
  – High bandwidth access to results
  – Voice recognition
Erosion

- Erosion is a numerical technique for combating element distortions in Lagrange meshes
  - Has no physical foundation
  - Erosion strains should be much larger than physical failure strains
- When the deformation of an element reaches a point where either the time step is significantly reduced or the element becomes degenerate (i.e. it inverts), the element is removed (eroded) from the analysis.
- When an element erodes
  - Its internal energy is always discarded
  - Its inertia can be retained as free mass points (not recommended for 2D axial symmetric impact)
Damping: Artificial Viscosity

Linear Viscosity (reduces noise) - Euler

![Graph showing pressure over time with different viscosity settings.](image)
“Hourglassing” is a deformation that produces no volume or strain change in hex / quad meshes.

- The numerical equations only involve differences in velocities and coordinates of diagonally opposite corners. If these differences remain constant, there is no change in the element volume / strain.

- A damping term is applied to resist this type of distortion.

**HE Detonation in Aluminum Cylinder**

Hourglass coefficient = 0.0

Hourglass coefficient = 0.1 (default)
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Thank You for Your Attention

Questions?

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