Recent and Ongoing Developments in LS-DYNA

Dilip Bhalsod

12th Oasys LS-DYNA Indian Update Meeting
March 2019
As of March 04, 2019 Nathan Asher Hallquist has been appointed Executive Vice President of LSTC.
Outline

• Introduction

• Applications and development updates on
  – Metal forming
  – Implicit
  – Frequency Domain Analysis
  – Material: composite
  – CFD: ICFD, ALE, SPH & CESE
  – Meshless method

• Summary & Future
Introduction
Growth of LS-DYNA

• Continues leading explicit FEA

• Keeps growing

Explicit CAE openings in Indeed, 05/04/2018

Global Market Share

CONFERENCE PAPERS

STAFF
## LS-DYNA Applications

### Development costs are spread across many industries

<table>
<thead>
<tr>
<th>Automotive</th>
<th>Structural</th>
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<tbody>
<tr>
<td>Crash and safety</td>
<td>Earthquake safety</td>
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<tr>
<td>NVH &amp; Durability</td>
<td>Concrete and composite structures</td>
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<td>FSI</td>
<td>Homeland security</td>
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<th>Electronics</th>
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<td>Bird strike</td>
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<td>Containment</td>
<td>Package analysis</td>
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<tr>
<td>Stamping</td>
<td>Weapons design</td>
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<td>Forging</td>
<td>Blast and penetration</td>
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<tr>
<td>Welding</td>
<td>Underwater Shock Analysis</td>
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<table>
<thead>
<tr>
<th>Consumer Products</th>
<th>Biosciences</th>
</tr>
</thead>
</table>

-Livermore Software Technology Corp.-
Forming Simulation

L. Zhang, X. Zhu, F. Ren
LS-DYNA for forming

- Users include, not limited to,
  - Audi, BMW, Volvo, Honda, Mazda, Nissan, Toyota, Unipres,..

- Usage of LS-DYNA for Metal Forming in BMW
  - cold forming, trimming and springback compensation
  - simulation of indirect press hardening.

LS-DYNA for forming in BMW


Draping of CFRP

Assembly process,

- Insertion of single parts
- Modeling of spotwelds, weldlines & adhesive
- Hemming simulation of the outer parts
MPP Fusion

• As per BMW’s request, Fusion is extended to MPP

• MPP performance
  – Reduce simulation time > 25%
  – Forming error < 2%
  – Springback error < 10%
Tube-adaptive method

• Box-adaptive method
  – Cannot handle arbitrary loading path
  – Need to perform mesh fission/fusion every single time step

• Tube-adaptive method
  – Arbitrary loading path
  – Optimal adaptive time interval and tube radius
  – Reduce computational cost while maintaining accuracy

<table>
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<tr>
<th>Radius</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>14</th>
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<tr>
<td>Thick. Diff. (%)</td>
<td>6.4</td>
<td>4.4</td>
<td>5.2</td>
<td>1.8</td>
<td>0.3</td>
<td>0.7</td>
<td>0.9</td>
<td>0.6</td>
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<tr>
<td>Time Red. (%)</td>
<td>50</td>
<td>50</td>
<td>49</td>
<td>47</td>
<td>46</td>
<td>45</td>
<td>44</td>
<td>40</td>
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</table>
Translational between FLD and Triaxial Limit

- Increasingly, as more Advanced High Strength Steels (AHSS) are being used, stamping engineers need to worry about material failure such as shear fracture during forming, in addition to the traditional necking failure.

- Two keywords are created to conveniently translate the two types of failure limits.
  - *DEFINE_CURVE_FLD_FROM_TRIAXIAL_LIMIT
  - *DEFINE_CURVE_TRIAXIAL_LIMIT_FROM_FLD

---

[Diagram showing the relationship between FLD and Triaxial Limit]
IGA for Metal Stamping

- NUMISHEET 2005 benchmark in 2017

**FEA:**
- Avg. mesh = 2mm
- 3.7 hr

\[ \varepsilon_{\text{max}}^p = 0.445 \]

\[ t_{\text{min}} = 1.35\text{mm} \]
\[ t_{\text{max}} = 1.85\text{mm} \]

**IGA:**
- No adaptivity
- Mesh = 4mm
- 2.2 hr

\[ \varepsilon_{\text{max}}^p = 0.381 \]

\[ t_{\text{min}} = 1.37\text{mm} \]
\[ t_{\text{max}} = 1.82\text{mm} \]
Implicit

Thomas Borrvall, F. Bengzon
LS-DYNA for Implicit analysis

- Spring-back compensation
- Static structure analysis
- Safety analysis
- Other:
  - Oil canning simulation
  - Door sag simulation
  - Frequency domain solver for NVH, fatigue, random vibration analysis..

F (t) = F_0 \sin(\omega t + \phi)

Fitting of rubber cylinder between two steel components, VOLVO GTT
Improvement for implicit

• Prescribed motion
  – exact integration of velocity and acceleration curves
  – avoid zero residual force for use on rigid bodies

• Mortar contact
  – frictional torque due to (shell) offsets
  – extensions of friction, tiebreak and tied weld
  – Rejections

• Prestress
  – initial stress section accounts for bending
    • IZSHEAR=2 on *INITIAL_STRESS_SECTION
  – mean cross sectional stress prescribed
  – preserves structural integrity of bolts
Improvement for implicit

- Process splitting (*CASE)
  - implicitly requested by users
  - a "complicated" process is divided into "simple" steps
  - each "step" is simple and clean
    - no birth/death, simple curves etc.
  - system state transferred between cases through dynain.lsad
    - stress, history, stabilization, contact friction, tied contact
  - flexible
    - each case is essentially a keyword input, allows for "any" modifications
  - "restart" can be made from any case
    - saves the agony of rerunning the entire process
Frequency Domain Analysis

Z. Cui & Y. Huang
Using MCMS for NVH analysis

MCMS (developed by Roger Grimes)

Multi-level Component Mode Synthesis

CPU cost for a large number of modes shows significant saving with MCMS.

SSD results by Lanczos

SSD results by MCMS
Time domain fatigue analysis

- Calculate damage ratio and fatigue life in time domain
- Advantages
  - A wide selection of stress / strain solvers (linear / nonlinear, thermal, multi-physics, fluid-structure interaction, EM, CFD, explicit / implicit, etc.)
  - Integration of vibration and fatigue solvers in one code.
IGA for Frequency domain SSD

**NURBS Shell Model**

*Full Gauss integration rule*

*Piecewise linear plasticity (*MAT_024)*

![NURBS Shell Model Diagram]

**FEA baseline model**

*Fully integrated shell with assumed strain formulation*

![FEA baseline model Diagram]

<table>
<thead>
<tr>
<th>Analysis tool</th>
<th>Number of elements</th>
<th>CPU (s)</th>
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<tbody>
<tr>
<td>IGA</td>
<td>1444</td>
<td>47</td>
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<tr>
<td>FEA</td>
<td>1444</td>
<td>6</td>
</tr>
<tr>
<td>FEA</td>
<td>5776</td>
<td>23</td>
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<tr>
<td>FEA</td>
<td>12996</td>
<td>54</td>
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</table>
Material
Composite
LS-DYNA composite material - application

- Traditional material model like MAT58 with CDM tends to underestimate the energy absorption (EA) by 10%~40%

- enhanced continuum damage mechanics (ECDM) model and a shell-beam (SB) method are developed as a remedy
LS-DYNA composite material - application

- Pre-preg compression molded (PCM) CF composites is modeled in meso-scale using MAT_54

![Diagram of composite ply (fiber orientations and materials) defined at integration points]

**Axial Dynamic Impact of Hat Section**

- Mass = 795kg
- Drop Height = 994mm
- Impact velocity = 4.413 m/s

![Graph showing impactor load (KN) vs. time (msec.)]

LS-DYNA composite material - application

- Draping and RTM

- Braiding

“Simulation of the Braiding Process in LS-DYNA”, Seyedalireza Razavi  
Imperial College London, Department of Aeronautics, London, UK  
15th International LS-DYNA® Users Conference
MAT_293 for the preforming of woven composites

- For woven prepregs forming simulation, which are woven CFRPs impregnated with uncured thermoset resin in desired fiber orientations
- Decouple the strong tension and weak shear behavior of the woven composite under large shear deformation
- For woven long fiber composite, fiber angle after forming is critical for accurate predication of crash performance
Short fiber from molding to crash

- New interface program to utilize Moldflow and MoldEx3D molding result for LS-DYNA crash analysis is recently implemented in LS-PrePost
- Enhance MAT_157 with *INITIAL_STRESS card for elasticity tensor $C_{ij}$

Fiber orientation result from Moldflow

LS-DYNA 3 point bending simulation
Thick shell and cohesive element for delamination

- Model description
  - CFRP modeled as thick shell; each thick shell represents a ply
  - Cohesive element thickness of 0.01mm; TS size 4mm x 4mm
  - Both UD and Woven tested
  - MAT_054 is used

V = 4.4 m/s

UD: 12 layers
Woven: 4 layers

3 point bending

3-point bending

Woven 0-90
Thick shell and cohesive element for delamination

Axial crush

3 point bending

Woven 45-45

UD [0/60/-60/0/60/-60]_S

UD [0/90/90/0/0/0]_S
One-Step Analysis for Woven Carbon Fiber Composite

- **DEFINE_FIBER**
  - defines carbon fibers and their related properties in a matrix for a one-step inverse forming simulation.
  - Can predict the desired composite shape and fiber orientations
  - works *only* with the keyword *CONTROL_FORMING_ONESTEP

![Diagram showing predicted shape and fiber angles](image)

Predicted shape and fiber angles:
- Target (blue) and Predicted (red) shapes
- Predicted fiber angles at 0, 90 deg and 45, 135 deg
*CONSTRAINED_BEAM_IN_SOLID

- Was designed for RC; Extended to simulate FRP manufacturing process
- Thermal-mechanical Adaptive EFG method with local refinement
CFD Technique

Zeng-chan Zhang, Kyoung-Su Im, and Grant Cook, Jr.
Hao Chen
Inaki Caldichoury, Pieree L’Eplattenier
Edouard Yreux
# CFD solvers in LS-DYNA

- Available CFD solvers in ls-dyna

<table>
<thead>
<tr>
<th>Solver</th>
<th>CESE</th>
<th>ICFD</th>
<th>ALE</th>
<th>SPH</th>
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<tbody>
<tr>
<td>Low speed aerodynamics</td>
<td>-</td>
<td>√</td>
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<tr>
<td>High speed aerodynamics</td>
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<td>Explosive with EOS</td>
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<td>Airbag-piston</td>
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<td>Free surface problem (slamming)</td>
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<td>FSI</td>
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<tr>
<td>Chemistry reaction</td>
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<tr>
<td>Stochastic particles</td>
<td>√</td>
<td>-</td>
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</tr>
</tbody>
</table>
ICFD applications

- Hood flutter vibration

Hood attached to a rotational spring

Extraneously induced excitation

“Instability induced excitation”

Flow field around the front of the following car

Pressure profile

Force on the hood of the following car

ICFD applications

- Stress on a deformable spoiler

- 2D simulation of a deformable hood

ICFD applications

- Airdrop simulation
Steady State Analysis for Conjugate Heat and FSI

The steady state solver or the potential flow solver allow for a fast linearization of Fluid Structure Interaction (FSI) and/or Conjugate Heat transfer (CH) problems.

Steady state analysis allows engineers to study physical problems in a time average fashion.

These simulations provide valuable insight faster useful for prototyping.
Steady State for Conjugate Heat and FSI

- Conjugate heat transfer for die cooling

- FSI

Navier Stokes

- Temperature
  - Time: 3 hours

Potential Flow

- Temperature
  - Time: 7 min

- Velocity
  - 24 hours

- Pressure
  - 20 minutes
Immersed Interface & sliding mesh

- Immersed interfaces
  - simplifies the pre-processing of complex geometries.
  - provide sharp interfaces and allow structural contact.

- Sliding mesh
  - for the simulation of transient rotating mechanisms without re-meshing.
  - the domain is split into at least two volume meshes. One mesh will have the rotating components and the other the rest of the domain
  - prevents excessive re-meshing in problems that involve rotating parts
Compare ALE and ICFD based on airfoil simulation

- Based on NACA0012

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"Computational Fluid Dynamic of NACA0012 with LS-DYNA (ALE & ICFD) and Wind Tunnel Tests", B.Perin 14th International LS-DYNA Users Conference
Boundary Layer and periodic boundary condition

- Boundary layer and new RANS turbulence model
  - improvements in speed and quality of boundary layer mesh generation
  - Most commonly encountered RANS Turbulence models are available

- Periodic boundary condition
  - allow a domain reduction of the areas with a repeating fluid pattern. It is widely used in the simulation of turbomachinery.
Coupling IGA with ICFD
ALE
S-ALE: Mesh Trimming

- ALE_STRUCTURED_MESH_TRIM trims off unnecessary elements.


<table>
<thead>
<tr>
<th>method</th>
<th># of ele</th>
<th>time</th>
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<tbody>
<tr>
<td>ALE</td>
<td>84800</td>
<td>1.0</td>
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<td>S-ALE</td>
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<tr>
<td>S-ALE_TRIM</td>
<td>43219</td>
<td>0.35</td>
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</table>

Results consistency

CPU time / MPP 4 cores
S-ALE: FOLLOW_GC & mesh merging

- New option of FOLLOW_GC of ALE_STRUCTURED_MESH_MOTION move the ALE mesh with the gravity center of certain AMMG groups; and expand/contract with those fluids.


- Multiple ALE_STRUCTURED_MESH cards. Can share the same PID
  - A finer mesh for HE and solid can share the same PID with the coarser air mesh separately created by other ALE_STRUCTURED_MESHES card

Two meshes setup reduced mesh usage from 6 million to 4 million.
S-ALE vs. ALE for blast simulation

• Save 28% of CPU with comparable results

Phase Change EOS for ALE FSI

- In order to simulate fast transient phenomena such as Water Hammers or UNDEX, one must take into consideration phase change.
- Homogeneous Equilibrium Model (HEM) is one of the “one-fluid models” where only the average flow is considered by solving a unique set of governing equations and it can be based on a pure phase model.

Figure 4: Absolute pressure at sensor PT6: Experimental results Tijsseling et al., [8], ( ), numerical results with elastic pipes (—).
Comparing SPH & ALE for UNDEX

ALE and SPH formulations for Fluid Structure Interaction: Shock waves impact, Ramzi MESSAHEL Université de Lille 2016

Original SPH

Refined SPH

Pressure contour

"ALE and SPH formulations for Fluid Structure Interaction: Shock waves impact", Ramzi MESSAHEL Université de Lille 2016
SPH: Murnaghan Equation of State, IFORM=15/16

- Model incompressible fluid with SPH elements
- Weakly compressible formulation to numerically reduce the sound speed, and consequently increase the time step size

Validation: 2D dambreak, free surface flow

SPH: 3D Validation of Murnaghan Equation of State

Contact Force on Obstacle

- Experiment
- Numerical

Validated in 2D and 3D formulations
Implicit SPH

- Implicit, incompressible SPH formulation allows larger timestep size
- Tailored for wading-type problems
- Example with 9.1 million particles:

Implicit SPH
Color-coded by velocity

Blender rendering
Dynamically Rebalanced SPH

- Re-decomposed the model several times during simulation using a full deck restart
- 30% of cpu saving is observe in a typical bird strike simulation
MLS-based SPH

- A formulation based on moving least-squares (FORM = 12) is implemented to improve the major drawbacks associated with SPH: tensile instability and essential boundary condition enforcement. Moving Least Square formulation.

CESE and Chemistry Solvers

Zeng-chan Zhang, Kyoung-Su Im, and Grant Cook, Jr.
CESE coupling with other LS-DYNA solvers

Stochastic Particle Solver
Explicit, Double precision

Thermal
Implicit
Double precision

Chemistry
Implicit reactions & Explicit transport
Double precision

Mechanical
Implicit Dynamics
Explicit
Double precision

CESE
Explicit
Double precision

Source terms: density, momentum, energy
Source terms: density, momentum, energy, EOS
Density, Temperature, EOS, Pressure, Internal energy,
Force
Heat Flux
Temperature
Displacement and velocity
The purpose of the blast relief wall is to vent the combustion gases and pressure resulting from a deflagration of an enclosure in offshore plant. Gas mixture consists of air and methane (CH4).
## Meshless & particle methods

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<th>Method</th>
<th>Authors</th>
</tr>
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<tr>
<td>SPH</td>
<td>J. Xu</td>
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<tr>
<td>ALE</td>
<td>H. Chen</td>
</tr>
<tr>
<td>DEM</td>
<td>H. Tang, B. Zhang</td>
</tr>
<tr>
<td>SPG</td>
<td>Y. Wu, C.T. Wu</td>
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<td>Peridynamics</td>
<td>W. Hu, B. Ren, C.T. Wu</td>
</tr>
<tr>
<td>XFEM</td>
<td>Y. Guo, C.T. Wu</td>
</tr>
</tbody>
</table>
Meshfree & Particle Methods in LS-DYNA

- **Discrete**
  - Explicit
    - DEM (Discrete Element Method)
    - CPM (Particle Gas)
    - PARTICLE_BLAST

- **Continuum**
  - Explicit Meshfree Collocation
    - SPH
  - Explicit Meshfree Galerkin
    - EFG, SOLID41&42, SHELL41~44
    - XFEM: SHELL52&54
    - MEFEM for nearly incompressible material, SOLID43
    - SPG (Smooth Particle Galerkin), SOLID47 for ductile failure
  - Implicit Meshfree Galerkin
    - EFG, SOLID41&42, SHELL41~44
    - MEFEM, SOLID43

- **Material Strength**
- **Velocity**
- **Momentum**

[Diagram showing various methods and their applications]
DEM

- for granular materials that consist of discrete particles like liquids and solutions, cereal, sand, toner,..
DEM: DE-DE contact improvement

- MPP scalability could deteriorate due to load imbalance when particles undergo large motion

- re-decompose for every N time steps

- Performance improvement

![Graph showing performance improvement with ideal speedup and Rebalance](image)

Different particle color represent different core
XFEM

- Most suitable for ductile materials in shell formulation, especially for pre-cracks
- A non-local algorithm is developed to minimize the mesh-size/orientation problems

Courtesy of Honda, JSOL Japan
Peridynamics Method

- **Extension of classical pdf-based equation.**

- **Most suitable for brittle materials in 3D solid formulation.**

- **Modified version formulated in Discontinuous Galerkin FEM**

- **Failure criteria is based on fracture energy released rate**
Peridynamics for windshield 3-point bending analysis

<table>
<thead>
<tr>
<th>Maximum Force (N)</th>
<th>Displacement (mm)</th>
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<td>Exp. 24.6</td>
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<td>Num. 26.0</td>
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</table>

Glass layers, MAT_ELASTIC_PERI

Courtesy of Tesla, USA
- Particle integration, able to handle severe deformation
- Most suitable for ductile materials in 3D solid formulation.
- Applications include machining, joining, cutting, riveting & drilling

**Experimental results**

**FEA**

**SPG**
Summary

- LSTC is working to be the leader in cost effective large scale numerical simulations
- LSTC is providing dummy, barrier, and head form models to reduce customer costs.
- LS-PrePost, LS-Opt, and LS-TaSC are continuously improving and gaining more usage within the LS-DYNA user community
- LSTC is actively working on seamless multistage simulations in automotive crashworthiness, manufacturing, and aerospace
- The scalable implicit solver is quickly gaining market acceptance for linear/nonlinear implicit calculations and simulations
- Robustness, speed, accuracy, and scalability have rapidly improved
Future

- New features and algorithms will be continuously implemented to handle new challenges and applications
  - Electromagnetics,
  - Acoustics,
  - Compressible and incompressible fluids
  - Isogeometric shell, solid elements and NURB contact algorithms
  - Discrete element methodology for modeling granular materials, failure, etc.
  - Peridynamics combined with EFG and DES
  - Composite material manufacturing
  - Modeling battery response in crashworthiness simulations
  - Sparse solver developments for scalability to huge # of cores, >10K
12th LS-DYNA European Conference

14 - 16 May 2019, Koblenz, Germany