Recent updates in linear solvers towards NVH and fatigue analysis in Ansys LS-DYNA®

Yun Huang, Tom Littlewood, Zhe Cui, Ushnish Basu, Francois-Henry Rouet, David Benson

Ansys

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A quick review of the NVH and fatigue solvers

Eigensolvers

- Lanczos
- MCMS
- LOBPCG
- Intermittent eigenvalue
- Pre-stressed eigenvalue

Vibration solvers

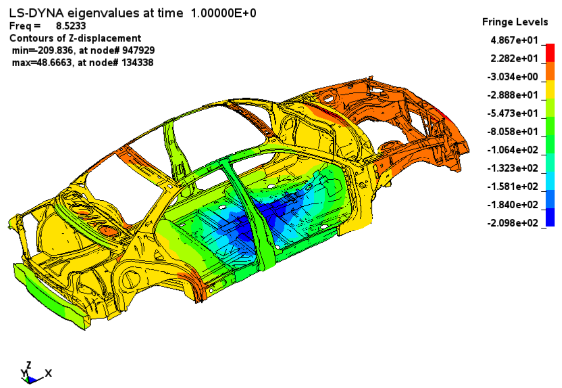
- FRF
- SSD
- Random Vibration
- Response Spectrum Analysis
- DDAM

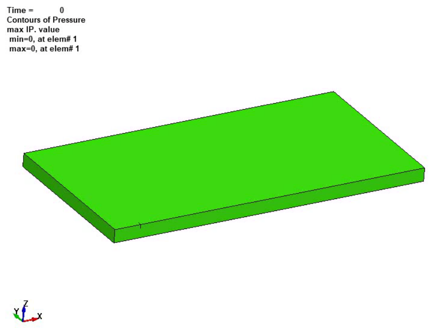
Acoustic solvers

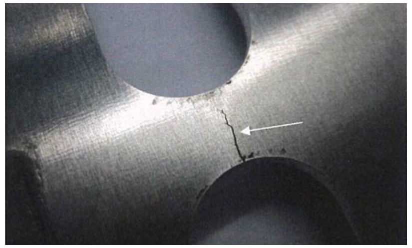
- Transient acoustics (FEM)
- Frequency domain BEM
- Frequency domain FEM
- Acoustic eigenvalue analysis
- Spectral element method
- Modal acoustics
- Statistical Energy Analysis
- Perfectly Matched Layer

Fatigue solvers

- SSD fatigue
- Random vibration fatigue
- Time domain fatigue
- Mean stress correction
- Multiaxial fatigue

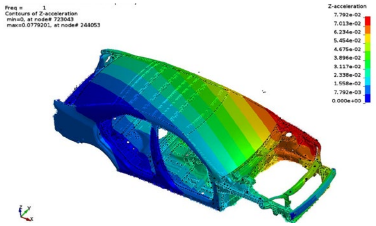


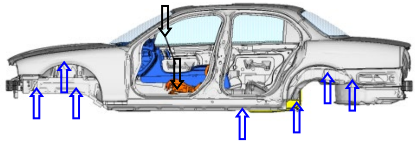


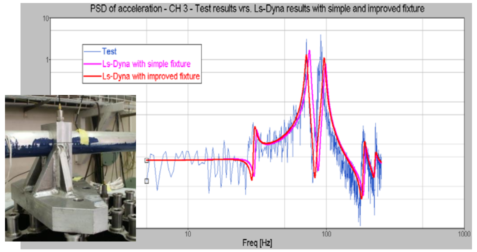


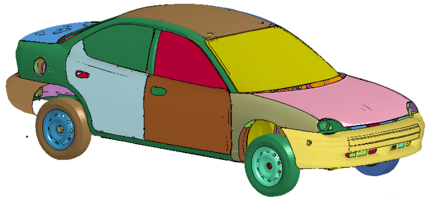
Capabilities

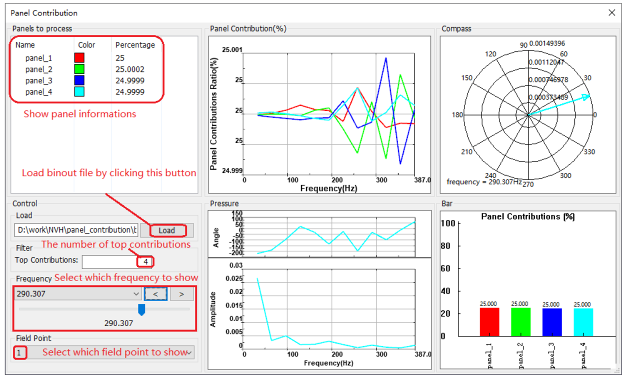
- Full body, trimmed body, BIW global modes (torsion & bending), dynamic stiffness, equivalent static stiffness, effective mass, etc.
- Shaker table testing simulation
  - Harmonic vibration (sine sweep)
  - Random vibration
- Vibration analysis with pre-stress
- Acoustic panel contribution analysis
- Muffler transmission loss analysis
- Vehicle pass-by noise
- Vibro-acoustics

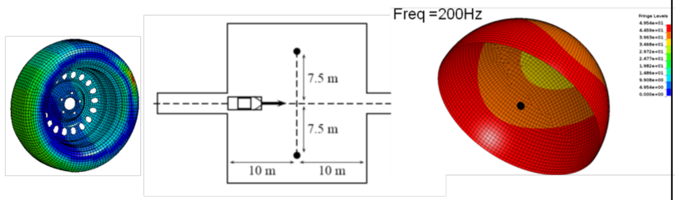




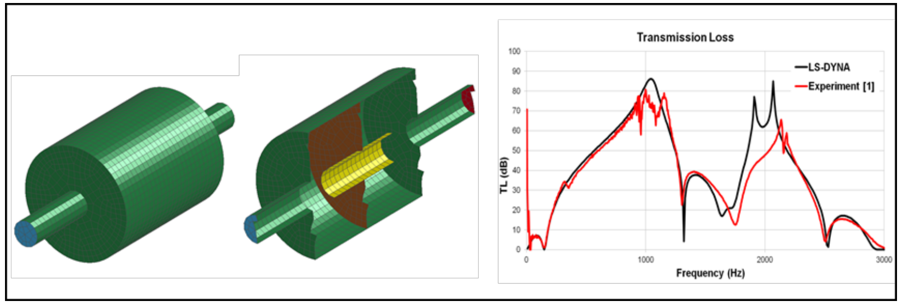






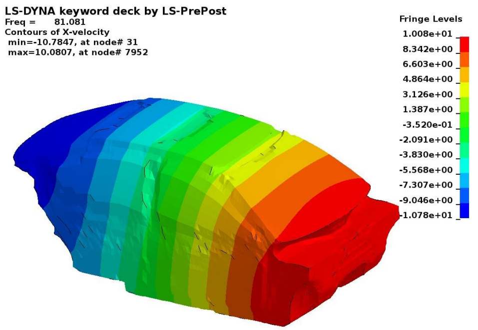


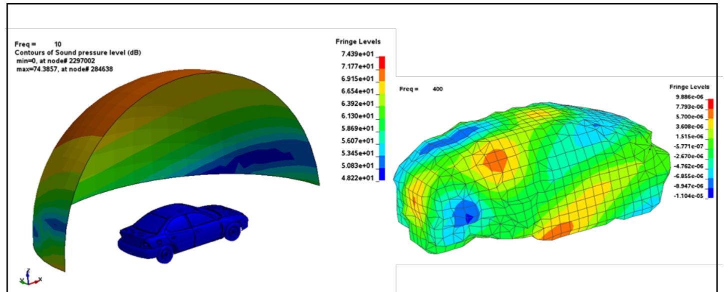
Pass-by noise test based on ISO 362 Standard



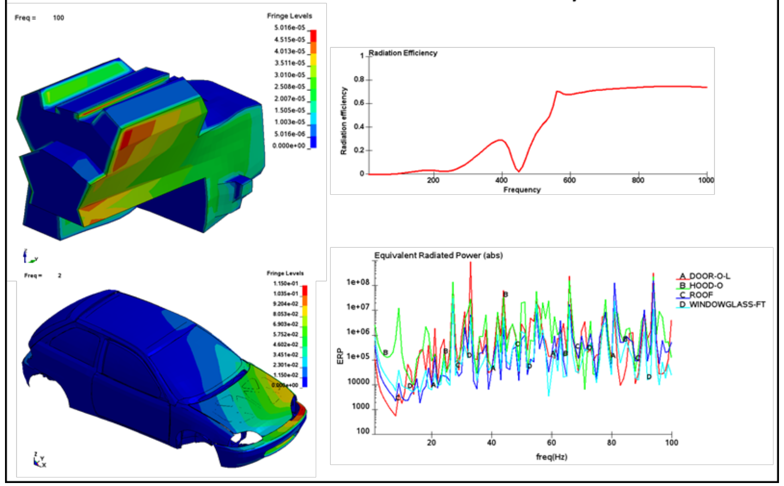
Capabilities

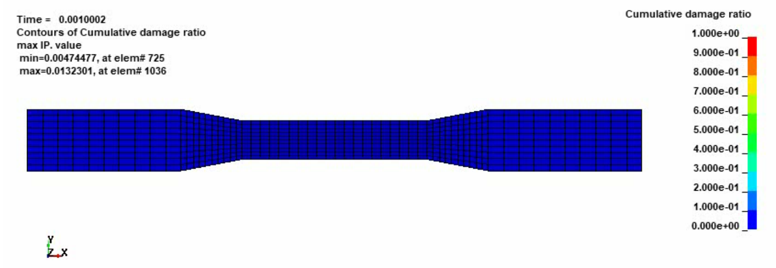
- Acoustic eigenmodes (cabin)
- Vehicle interior and exterior noise
- Acoustic transfer vectors
- Equivalent radiated power, radiation efficiency
- Coupling of fatigue and dynamic analysis
- Fatigue analysis based on stress and strain
- Multiaxial fatigue, mean stress correction, etc.
- Progressive fatigue failure modeling

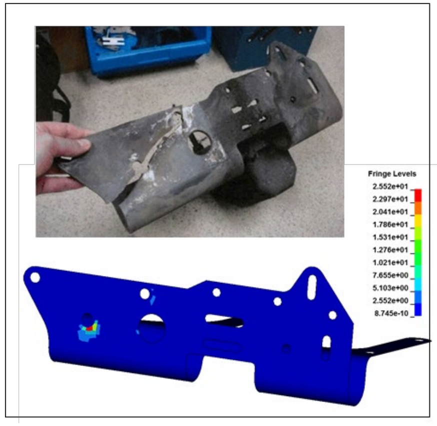


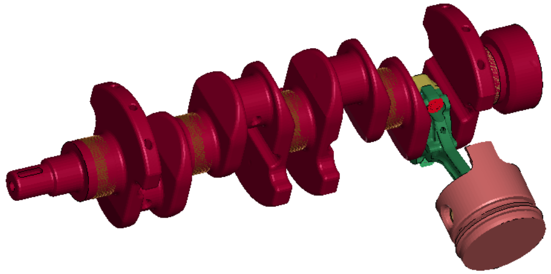

BEM works for both exterior and interior acoustics

ERP and radiation efficiency



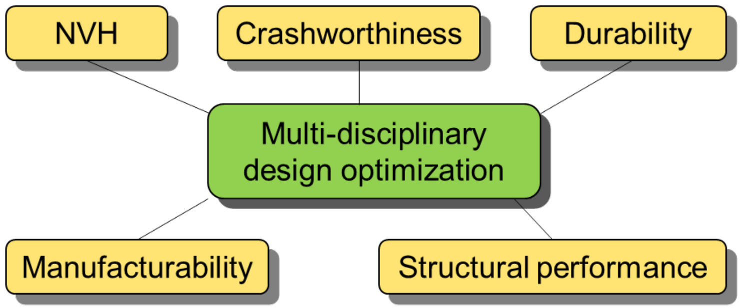


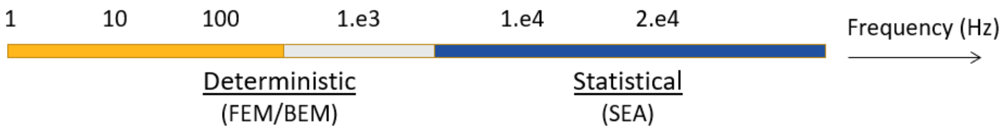




Features

- A common model approach
  - based on LS-DYNA crash analysis model
  - save model conversion / translation
  - facilitate multidisciplinary design optimization
- A complete suite of acoustic analysis methods (FEM, BEM, SEA, SEM, ERP, etc.)
  - From time domain to frequency domain
  - From low frequency to high frequency
  - From interior to exterior
  - From near field to far field
- Seamless coupling / integration with other Multiphysics solvers in LS-DYNA



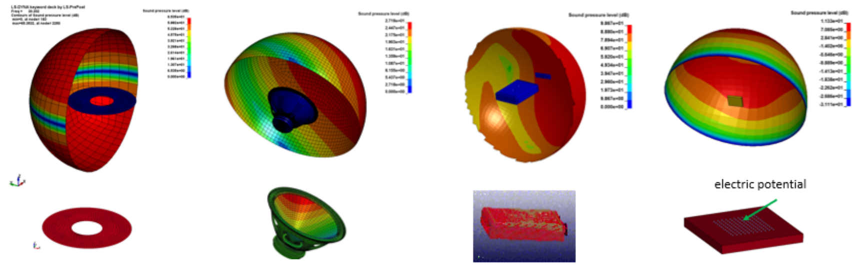


Spinning disc noise: coupling with rotor dynamics solver (Liping Li, Roger Grimes)

Speaker sound: coupling with EM solver (Pierre L'Eplattenier, Inaki Caldichoury)

Tank sloshing noise: coupling with ALE solver (Hao Chen, Nicolas Aquelet, Ian Do)

Piezo acoustics: coupling with PZT solver (Isheng Yeh, Xiaomeng Tong)



Overview of recent updates

Summary of recent updates

Acoustics	• Implementation of *FREQUENCY_DOMAIN_AOUSTIC_DIRECTIVITY to create acoustic directivity plot from BEM computation
	• Improvement of performance
	    • Improved SMP for variational indirect BEM
	    • Fast matrix assembly for variational indirect BEM
	• New options and boundary conditions
	    • sound absorption coefficient boundary
	    • symmetric boundary
	    • option _POWER to calculate and output acoustic power
	    • restart to get acoustic results for new locations

Random vibration	• OASPL computation for random pressure and plane wave load • GRMS computation for base acceleration PSD load
FRF / SSD	• support new loading (torque and base rotational motion) in FRF / direct SSD • NODOUT_SSD & ELOUT_SSD for direct SSD with frequency-dependent material properties
ERP	• support frequency-dependent ERP radiation loss factor • performance improvement by allowing running ERP without SSD output
d3max	• support ALE output in d3max

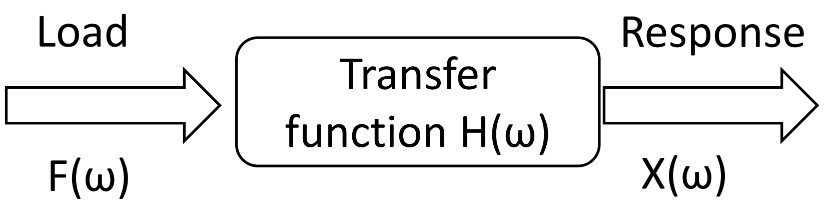
Summary of recent updates

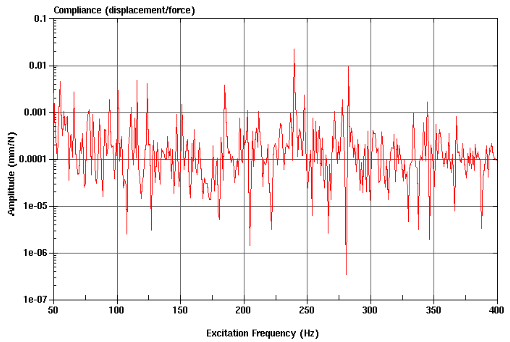
Fatigue	• Added counted cycles for fatigue in d3ftg • Added Steinberg’s method with peak crossing frequency • Integration of fatigue damage and material damage (GISSMO) for total damage ratio (e.g. for battery damage)

Introduction of the updates

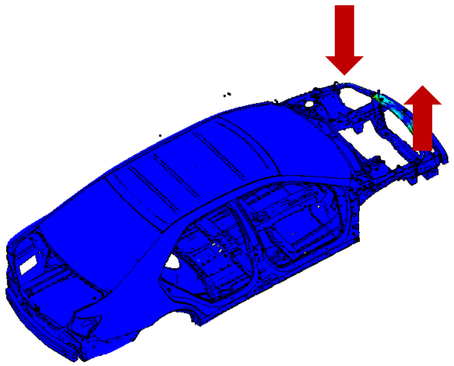
FRF: Torsion loading

- FRF (Frequency Response Function) calculates transfer function between load and dynamic response of a system, for a specified range of frequency.
- FRF can provides estimation of dynamic stiffness, effective mass, etc. for BIW, trimmed body, etc.
- Updates
  - Added torsion loading for FRF
  - Fixed bug in converting pressure to nodal force load
  - Enabled using structural damping in FRF





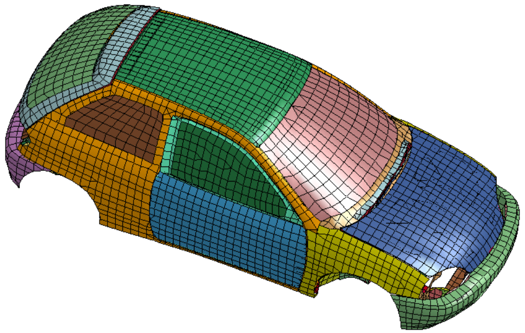

```
*FREQUENCY_DOMAIN_FRF
$#      n1     n1typ      dof1      vad1       vid     fnmax     mdmin     mdmax
       131         0         3        12         0 2000.0000         1        20
       144         0
$#   dampf     lcdam     lctyp    dmpmas    dmpstf
  0.010000         0         0     0.000     0.000
$#      n2     n2typ      dof2      vad2    relatv
         1         1         3         1         0
$#    fmin      fmax     nfreq    fspace    lcfreq    restrt    output
  1.000000 400.00000       400         0         0         0         0
```



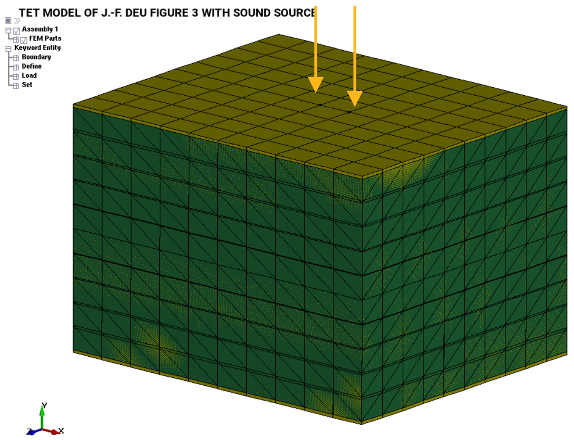
SSD: coupled fluid-structure system

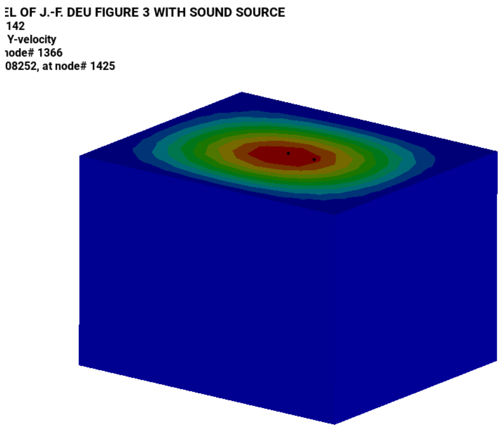
*CONTROL_IMPLICIT_SSD_DIRECT

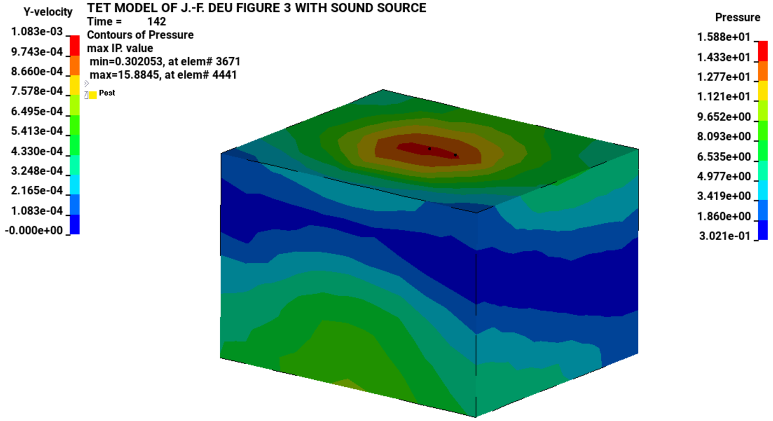
- Direct, complex solution to steady state vibration of coupled acoustic fluid and structure system
- Acoustic solid element ELFORM 8 and 14 may be used
- The coupling of the acoustic fluid and the structural elements is achieved with *BOUNDARY_ACOUSTIC_COUPLING_MISMATCH or by merging acoustic and structural nodes with compatible element faces
- Useful for the cases when interaction between the fluid and the structure need to be considered (cabin noise)



Nodal force excitation (75-500 Hz)





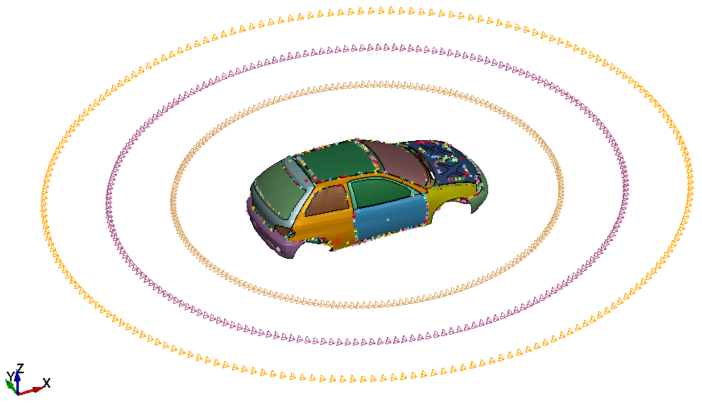


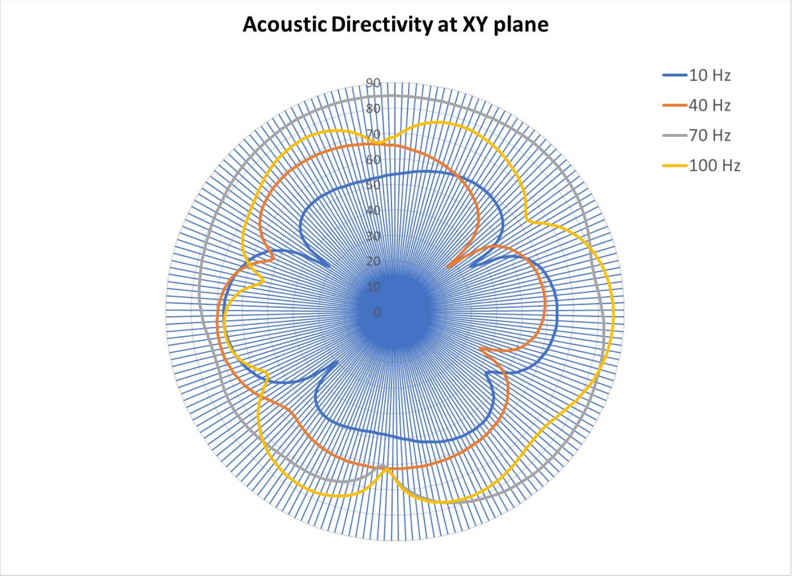
BEM acoustics: acoustic directivity plot

- Plot files are provided to show acoustic directivity
- Keyword: *FREQUENCY_DOMAIN_ACOUSTIC_DIRECTIVITY
- Multiple directivity plots can be provided
- Acoustic_directivity_node.k is generated to show the location of the nodes

```
*FREQUENCY_DOMAIN_ACOUSTIC_DIRECTIVITY
$#  center     radius         np    normal     angle0         x0         y0         z0
         1        10.        361         1
```

```
*SET_NODE_LIST_GENERATE
      2008
     51416     51616
*SET_NODE_LIST_GENERATE
      2009
     51617     51817
*NODE
   50009      -0.0000665      3.9993709      0.2871537
   50010      -0.0000665      3.9952047      0.4127432
   50011      -0.0000665      3.9870956      0.5381398
   50012      -0.0000665      3.9750518      0.6632198
   50013      -0.0000665      3.9590850      0.7878598
   50014      -0.0000665      3.9392111      0.9119368
```





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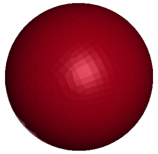
Acoustic directivity plot: validation with APDL

13.11. Example: Monopole Incident Wave Scattering of a Rigid Sphere

This example problem demonstrates the use of FLUID221 to predict the acoustic scattering of a monopole incident wave of a rigid sphere (radius = 1 m).

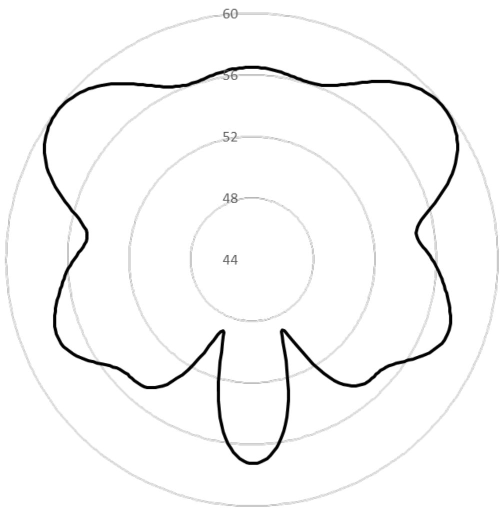
The monopole spherical source is located at (2, 0, 0).

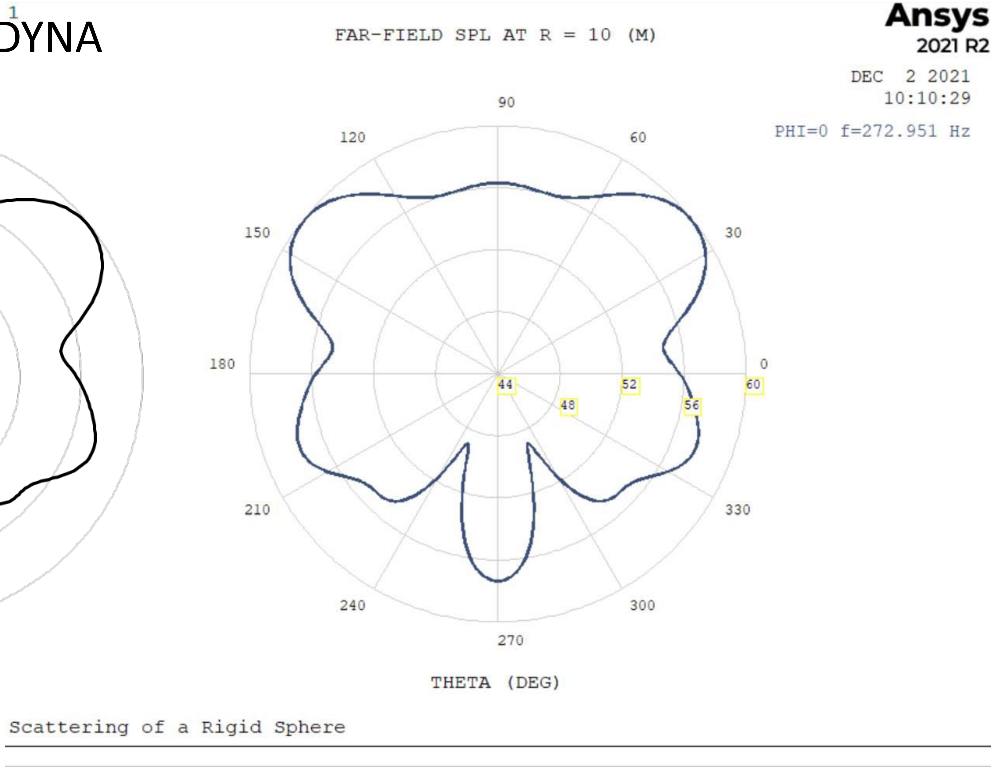
PML is used for truncation of the open space.



```
*FREQUENCY_DOMAIN_ACOUSTIC_BEM
$#      ro         c      fmin      fmax     nfreq    dt_out   t_start      pref
      1.21     343.0  272.9507  272.9507         1      0.00     0.000 2.000E-05
$# nsidext   typeext   nsidint   typeint    fftwin     trslt    ipfile    iunits
         2         1         0         0         4                   1
$#  method     maxit       res       ndd     tollr    tolfct     ibdim       npg
         2      1000 1.0000E-6         8
$#               nbc    restrt     iedge      noel     nfrup
                   1
$#    ssid    sstype      norm  bem_type       lc1       lc2
         1         2         0         3       100
*FREQUENCY_DOMAIN_ACOUSTIC_INCIDENT_WAVE
$#    type       mag        xc        yc        zc
         2       0.2       2.0         0         0
*FREQUENCY_DOMAIN_ACOUSTIC_DIRECTIVITY
$#  center    radius        np    normal    angle0        x0        y0        z0
         1       10.       361         1
```

Directivity by LS-DYNA





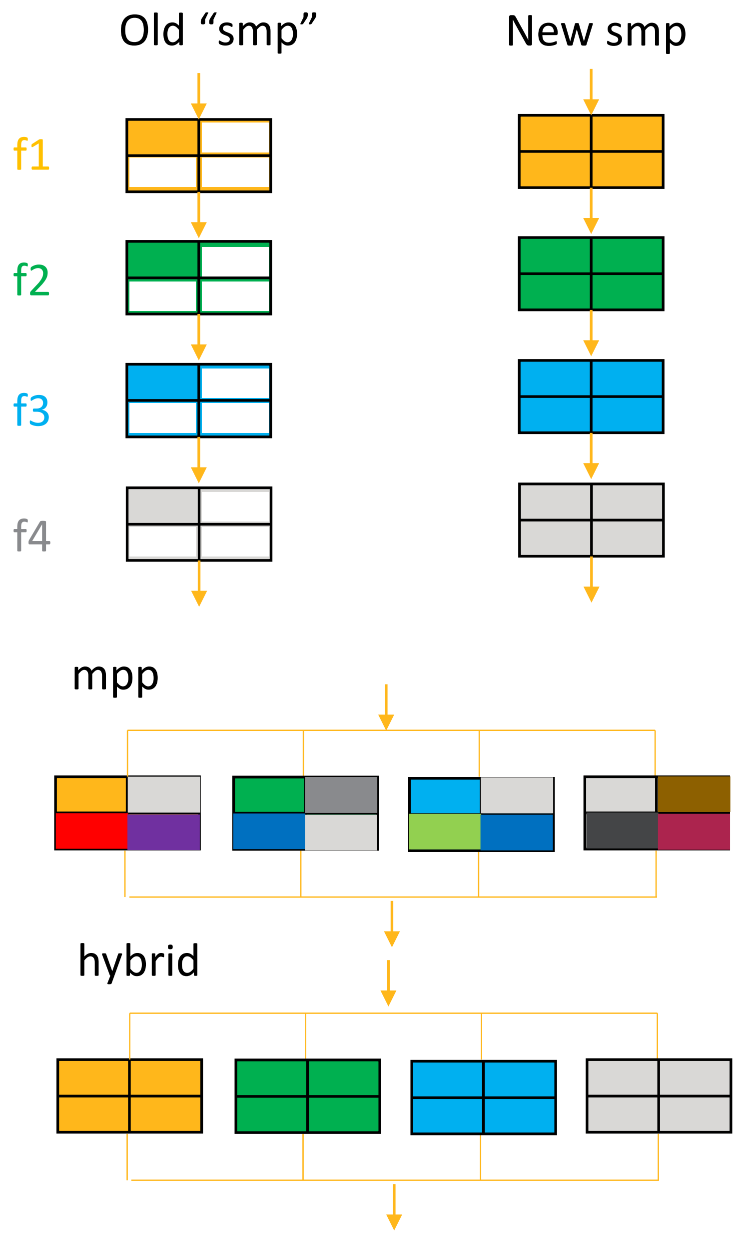
BEM acoustics: SMP improvements

- The Acoustics BEM is parallelized over frequencies with MPI.
  - This scales OK for large no. of frequencies (#freq > #MPI ranks).
  - Memory can be an issue because each MPI rank has a matrix etc.

- Prior to R13, each individual frequency solve was serial.

- In R13, parallelized matrix assembly with OpenMP.
  - Conceptually easy, loop over independent matrix blocks.
    (In practice, had to rewrite some code, make it thread safe, etc.)
  - Now we can do hybrid parallelism, MPI+OpenMP. Better for memory and scalability.

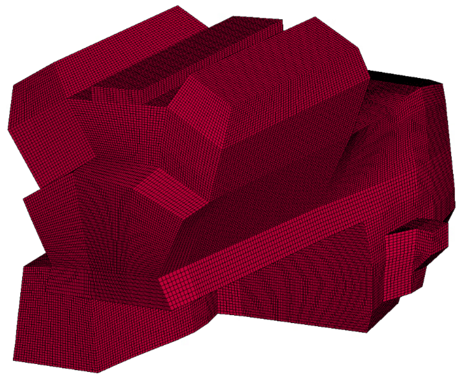
- For R14, improved parallelization of assembly and parallelized the linear solver (GMRES).

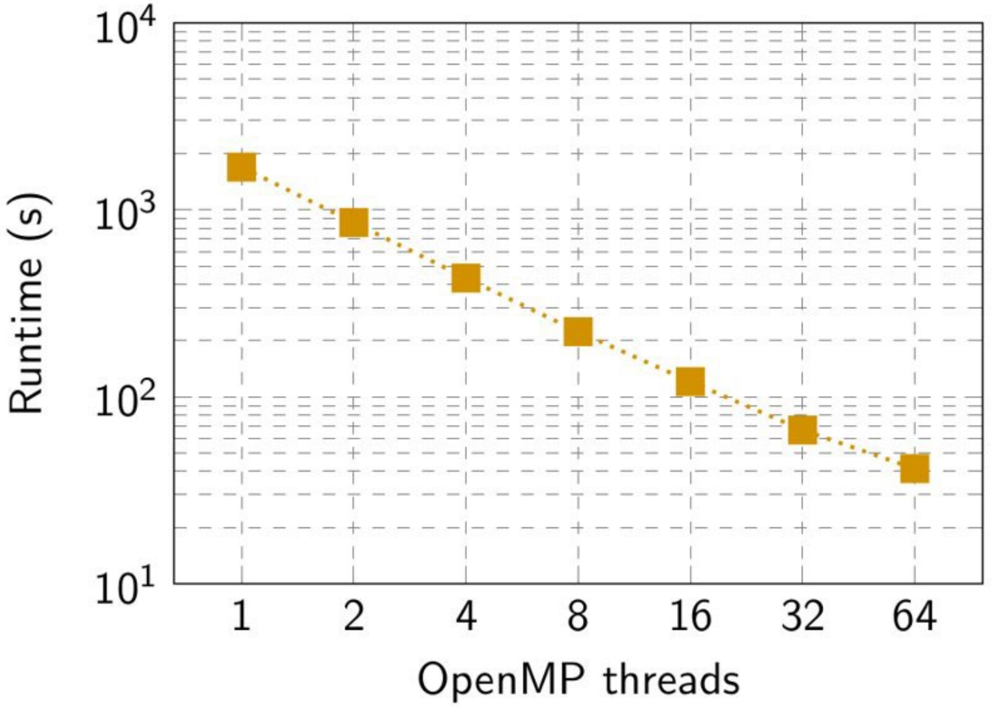


BEM acoustics: SMP improvements – example

Experiment:
- LS-DYNA Dev/R14;
- Four Intel Xeon Gold 6242 (4x16 cores);
- Engine block model, 78k dofs;
- Speed-up of 41 out of 64 using OpenMP.

Notes:
- Very scalable;
- Almost no memory overhead;
- Can be combined with MPI for multiple frequencies. Advice to users is (probably) one MPI rank per node, one thread per core.





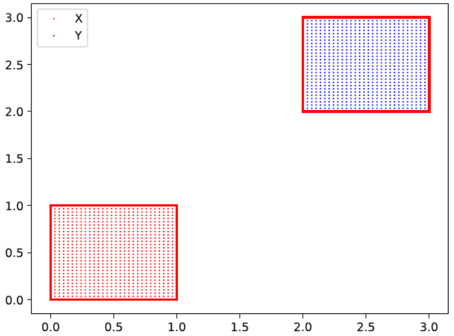
BEM acoustics: Fast matrix assembly by SI

Performance bottleneck:

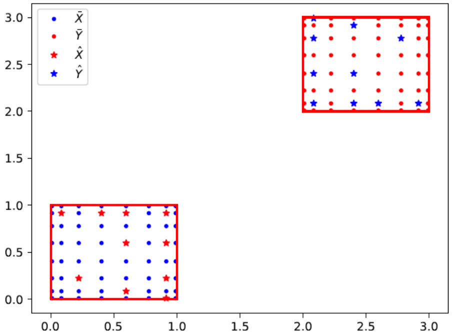
- In the past, matrix blocks are fully evaluated and then compressed into low-rank form. Essentially, we "throw away" most of the entries we evaluate.
- Over 90% of cpu time is spent evaluating matrix entries.

Skeletonized Interpolation (SI):

- SI is a sampling technique that allows building the compressed form without evaluating all the matrix entries. Less evaluations => faster.



(a) Geometry and mesh. Each square contains $30 \times 30 = 900$ uniformly distributed points.

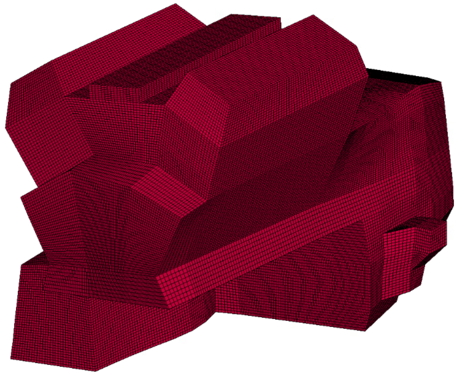


(b) Chebyshev tensor grids for $\epsilon = 10^{-6}$ and re-compressed nodes by SI.

BEM acoustics: Fast matrix assembly – examples

Results for two models:

- Engine block model, 78k dofs:
  SI speeds-up assembly by a factor 2.5x.
- Cabin model from ACE, 240k dofs:
  SI speeds-up assembly by a factor 5x.



Notes:

- Memory usage is unchanged.
- Solution vector is slightly different but same quality.
- In R14 it is the default method.

BEM acoustics: a quick restart to get results for more field points

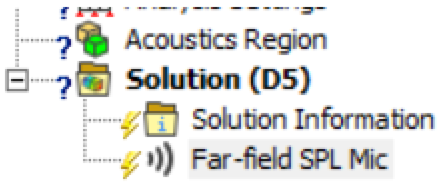
run jobs	# of field pts	# of CPUs	Total CPU cost
original run	1	24	46 min 34 sec
restart run	9	1	0.3 sec

Suggestion from Ansys WB team:

I have joined Simon's team where I will be able to spend more time developing the Acoustic BEM workbench platform. One thing we were wondering is if it was possible to define the measurement point after the solve.

In the current workflow we define a node as a measurement point before solving, which means that the user must know where the pressure will be measured before solving. Would it be possible for the user to define this point after the solve and to retrieve the pressure at this location?

This process is the one currently used in APDL Harmonic Acoustic, where a microphone is created after the solve and a routine compute the pressure at this point based on the pressure on the mesh.




```
*FREQUENCY_DOMAIN_ACOUSTIC_BEM
$#        ro          c      fnmin      fnmax      nfreq     dt_out    t_start       pref
  1.1889E-7   13169.26     1000.0     1010.0                 2.5E-5        0.0  2.900E-9
$#nsid_ext   type_ext   nsid_int   type_int    fft_win      trslt     ipfile     iunits
        10          1          0          0          5          0          0          0
$#  t_hold      decay
       0.0       0.02
$#  method      maxit   tol_iter        ndd     tol_lr   tol_fact      ibdim        npg
        21       1000   1.000E-6          8      0.000      0.000          0          0
$#                nbc     restrt      iedge       noel      nfrup
                    1          2
$#    ssid     sstype       norm   bem_type        lc1        lc2
         1          2          1          1
```

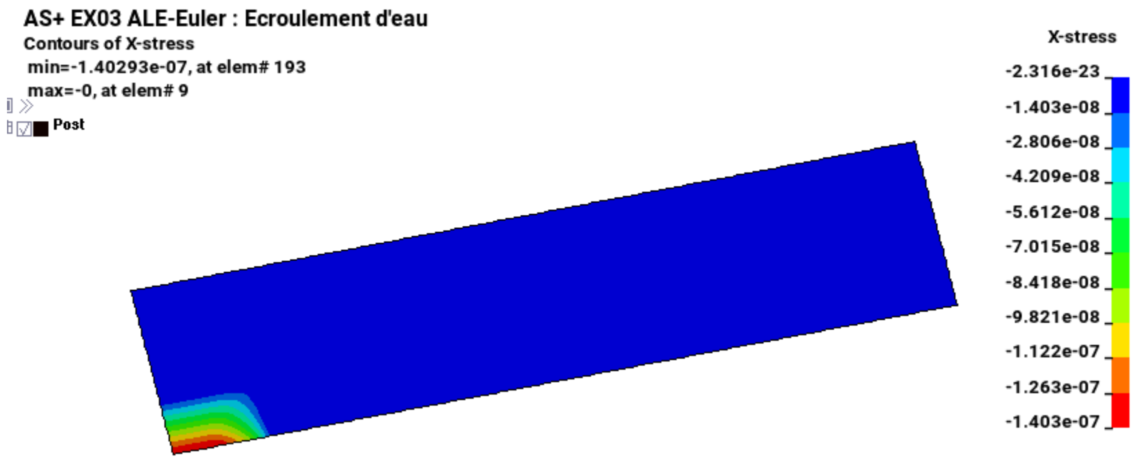
```
 T i m i n g   i n f o r m a t i o n
                          CPU(seconds)    %CPU  Clock(seconds) %Clock
  ----------------------------------------------------------------
  Keyword Processing ... 9.7583E-02    25.31    9.7585E-02    16.76
    KW Reading ......... 5.1140E-02    13.27    5.1142E-02     8.78
    KW Writing ......... 1.0922E-02     2.83    1.0922E-02     1.88
  Initialization ....... 2.2386E-01    58.07    4.2051E-01    72.23
    Init Proc Phase 1 .. 1.5331E-01    39.77    2.4815E-01    42.63
    Init Proc Phase 2 .. 3.6507E-02     9.47    1.0854E-01    18.65
  BEM Acoustics ........ 6.4064E-02    16.62    6.4065E-02    11.00
    Field output ....... 2.9095E-02     7.55    2.9095E-02     5.00
  ----------------------------------------------------------------
  T o t a l s            3.8550E-01   100.00    5.8216E-01   100.00

 Problem time       =    0.0000E+00
 Problem cycle      =          0
 Total CPU time     =          0 seconds (   0 hours  0 minutes  0 seconds)
```

d3max: support of ALE results

- ALE pressure is saved as negative stress results for solid elements.

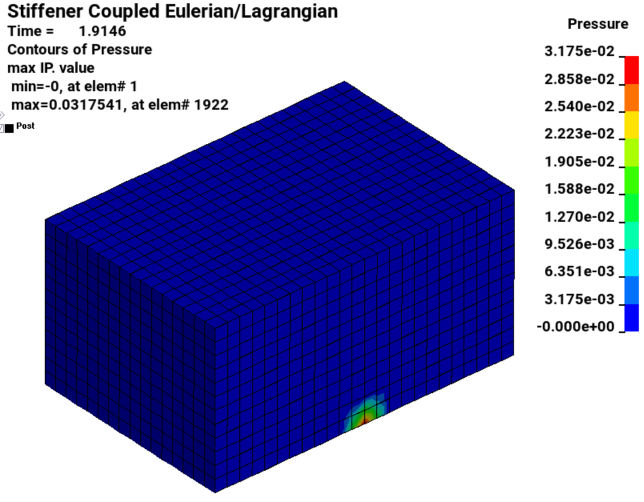
```
*DATABASE_D3MAX
$# dtcheck        me      pstrs      pstrn      ifilt     output    fcutout
     0.001                                                    3
*DATABASE_MAX_SHELL_SET
$#     id1        id2
         1
*SET_SHELL_GENERAL
         1
  ALL
```

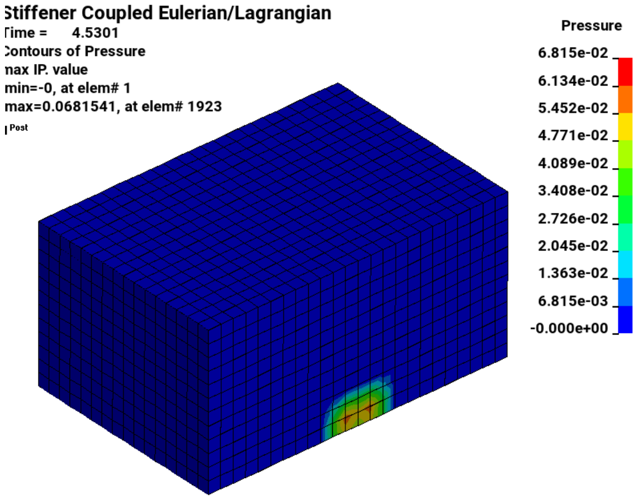
Thanks to Hao Chen, Nicolas Aquelet and Nikolay Mladenov for their help.

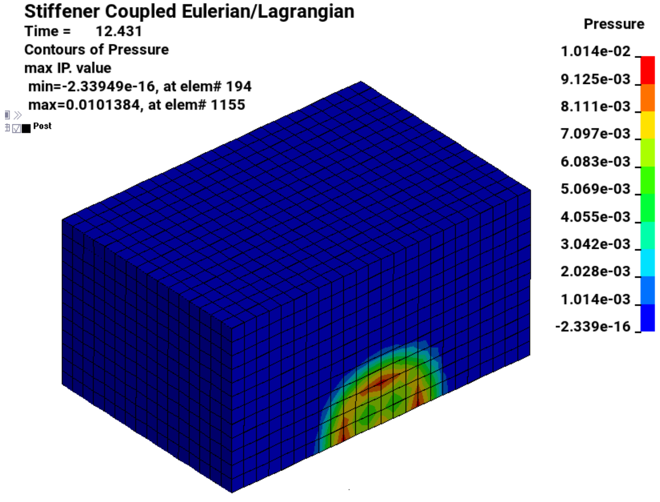


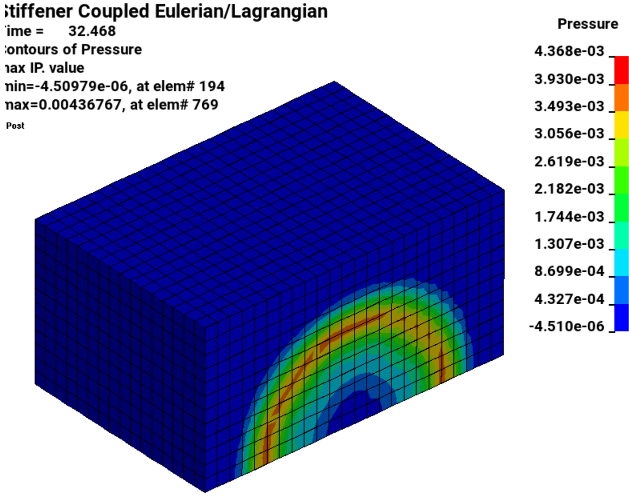
OUTPUT	Output format and flag to determine whether minimum or maximum values are output:
	EQ.0: Write maximum stress / strain to d3max
	EQ.1: Append the maximum stress / strain results to d3part
	EQ.2: Write the maximum stress / strain results to d3part instead of the normal data that goes into d3part (negative time stamps are used in d3part to distinguish when this is done from the normal d3part output, which saves time history results for selected parts)
	EQ.3: Write minimum stress / strain to d3max
	EQ.4: Append the minimum stress / strain results to d3part
	EQ.5: Write the minimum stress / strain results to d3part instead of the normal data that goes into d3part (negative time stamps are used in d3part to distinguish when this is done from the normal d3part output, which saves time history results for selected parts

d3max: support of ALE results







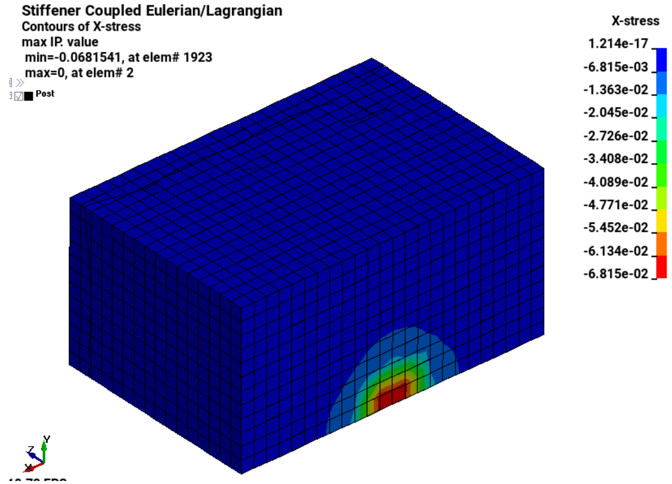


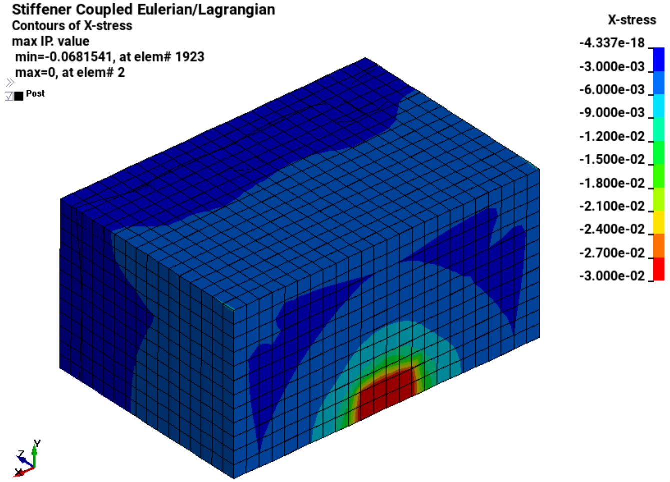
Initialization of the initial pressures due to an explosive disturbance

***INITIAL_DETONATION**

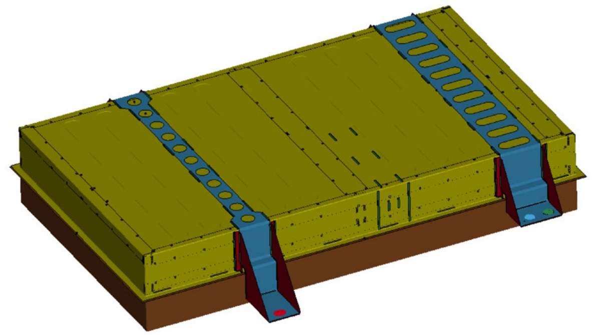
***MAT_HIGH_EXPLOSIVE_BURN**

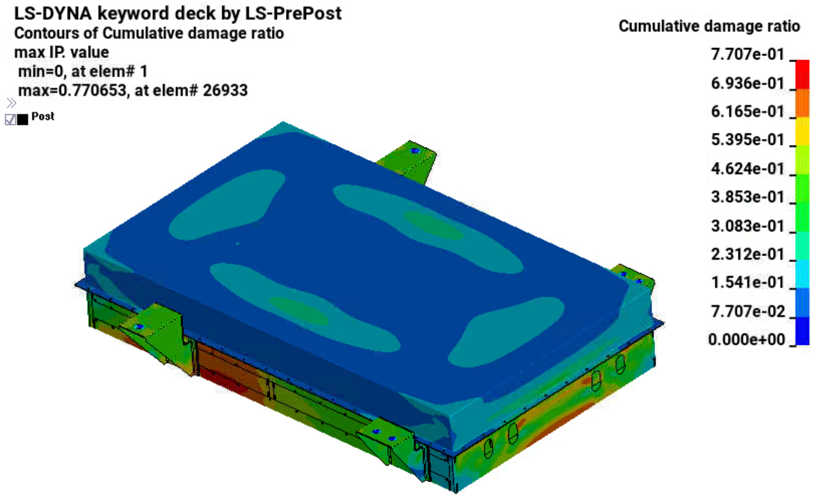
d3max

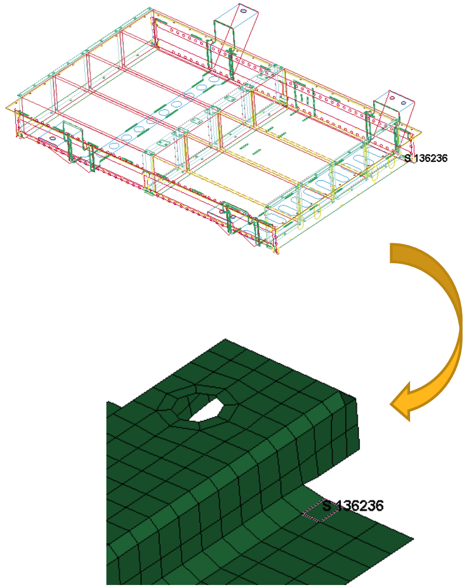




Fatigue: integration with material damage for battery safety analysis

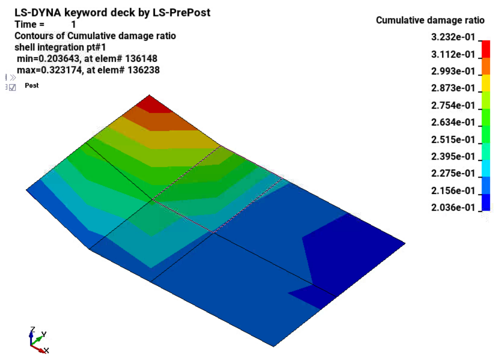




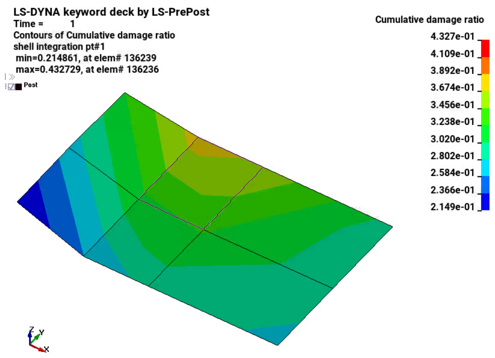


1. Run transient damage analysis from impact;
   - Residual stress saved in dynain
   - Damage from GISSMO model saved in d3plot
2. Run random vibration fatigue analysis;
   - Pre-stressed eigenvalue analysis with dynain
   - Random vibration fatigue analysis with base acceleration PSD
   - Damage from GISSMO model is included as initial damage ratio

<u>Without GISSMO damage</u>



<u>With GISSMO damage</u>



Thanks to Tobias Erhart & Daniel Wang for their help.

Summary and Future work

Summary

- A lot of updates and improvement have been introduced in the linear solvers in LS-DYNA during the past few years
  - Vibration solvers (FRF, SSD)
  - Acoustic solvers (directivity plot, SMP and SI, restart)
  - D3max (support ALE results)
  - Fatigue solvers (integration with material damage for battery safety analysis)
- We benefit from suggestions and feedback from users and ACE teams

Future work

- “One button conversion” to provide an easy conversion from LS-DYNA crash analysis model to NVH model
- Integration to Ansys WB platform
- Extension of acoustic spectral element method to frequency domain
- FEM-BEM coupled acoustic analysis
- Ray tracing acoustics (room acoustics)
- Adaptive meshing for acoustics (based on frequencies)

Thank you

Ansys

Ansys