Recent updates in LS-DYNA NVH solvers

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Outline

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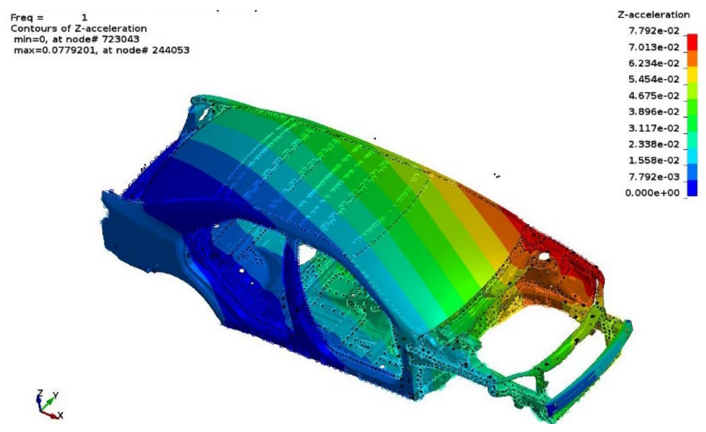
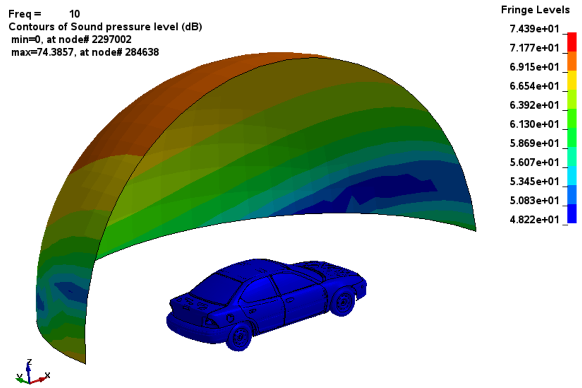
  - *SSD*
  - *Random vibration*
  - *Response spectrum analysis*
  - *Fluid added mass*
  - *Acoustic analysis by spectral element method*
  - *Acoustic analysis by boundary element method*
  - *d3max*
- Conclusion





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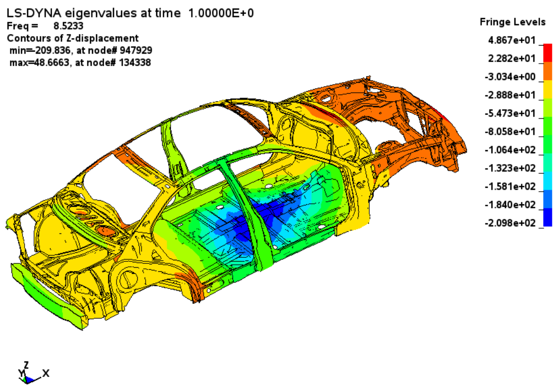
Overview of the NVH solvers in LS-DYNA

NVH solvers in LS-DYNA

Eigensolvers

(Roger Grimes, Francois-Henry Rouet)

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

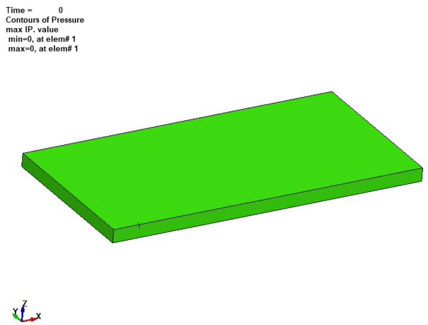


Vibration solvers

- 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



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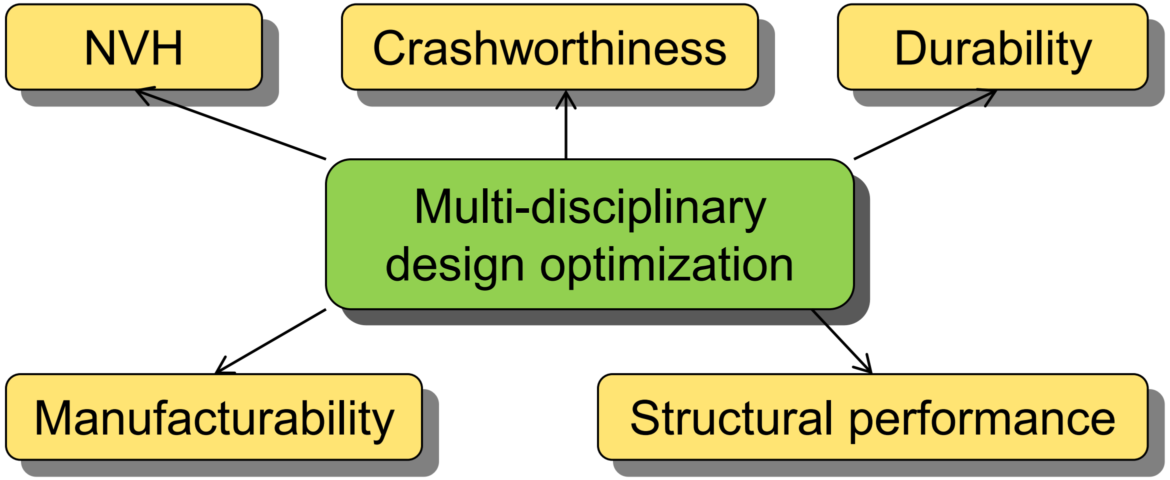
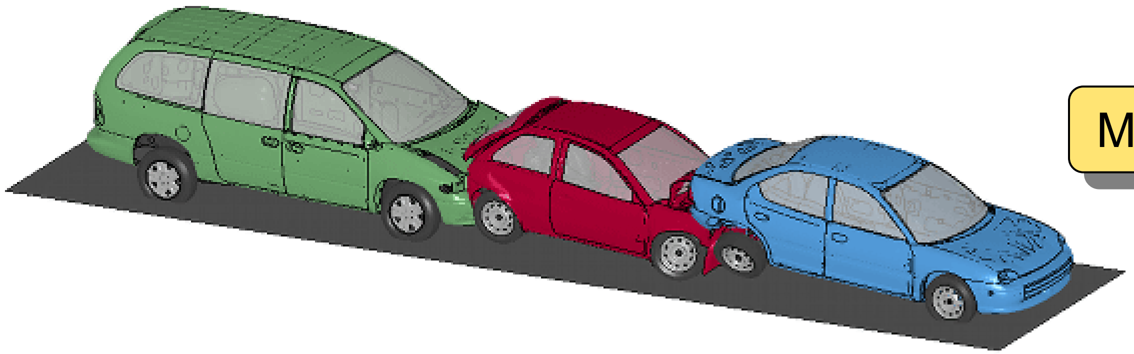
Motivation

- Demand on NVH (Noise, Vibration and Harshness) analysis from auto customers
- Certain features (material models, connections, etc.) in LS-DYNA models are not supported in other codes
- Multi-disciplinary Optimization





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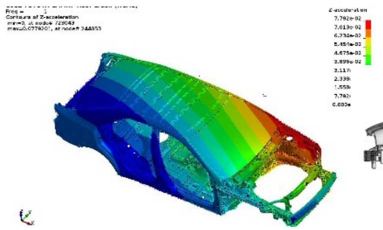
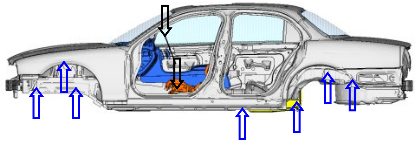
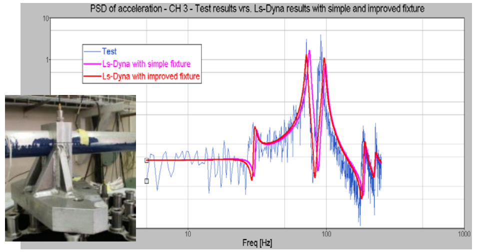
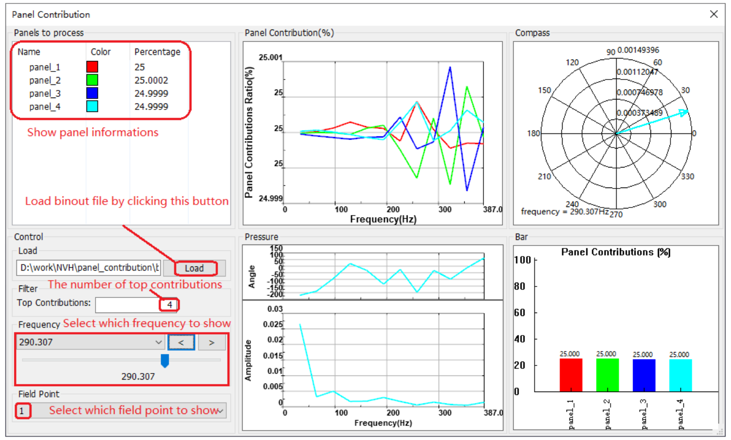
Capabilities

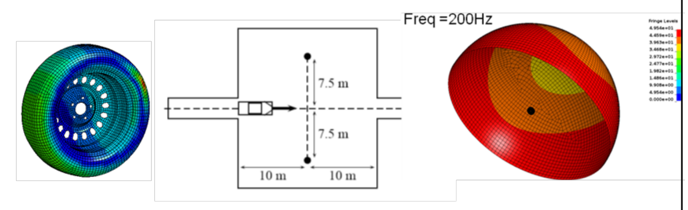
- Full body, trimmed body, BIW global modes (torsion & bending), dynamic stiffness, equivalent static stiffness, effective mass, etc.
- Shaker table testing simulation
  - Harmonic vibration (sine sweep)
  - Random vibration
- Vibration analysis with pre-stress
- Acoustic panel contribution analysis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



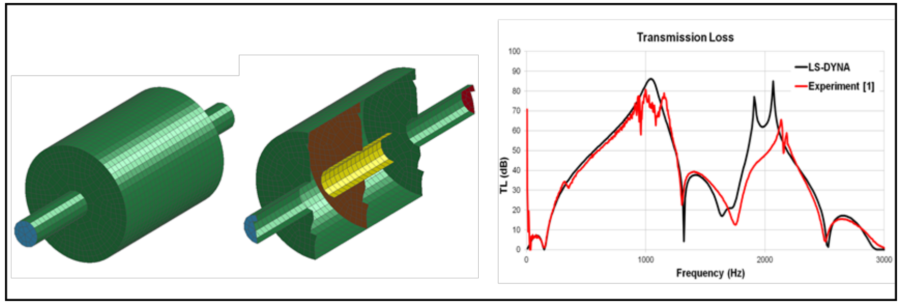








Pass-by noise test based on ISO 362 Standard



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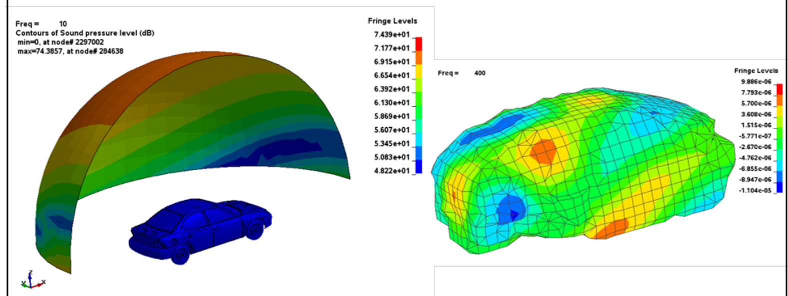
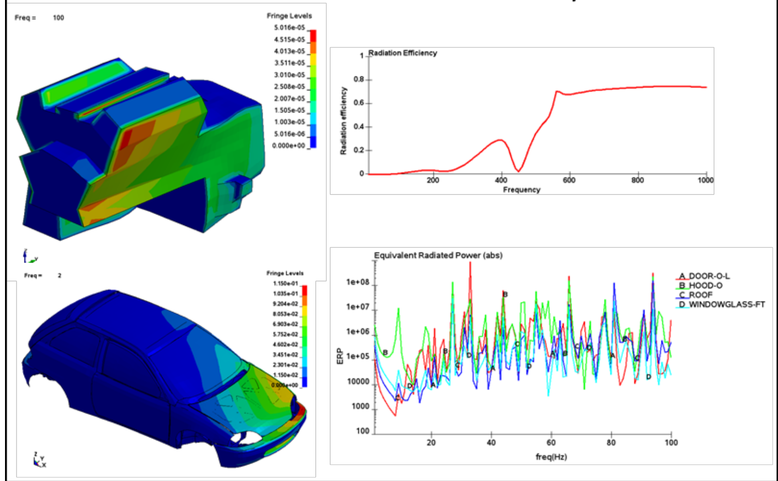
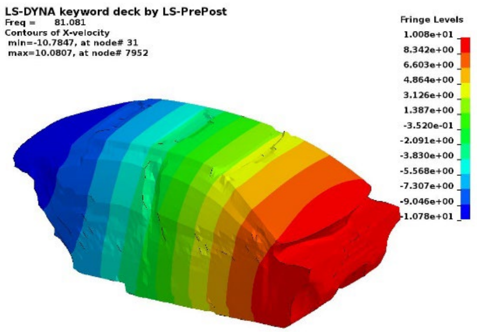
Capabilities

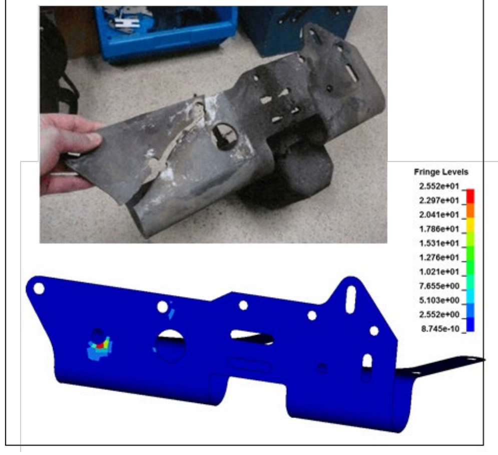
- Acoustic eigenmodes (cabin)
- Vehicle interior and exterior noise
- Acoustic transfer vectors
- Equivalent radiated power, radiation efficiency
- Vibro-acoustic analysis
- Vibro-fatigue analysis
- SMP and MPP versions



BEM works for both exterior and interior acoustics

ERP and radiation efficiency






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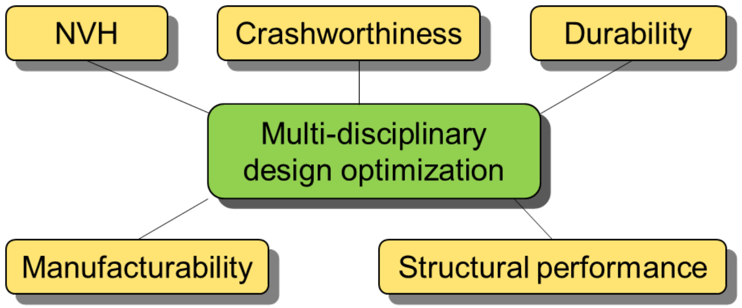
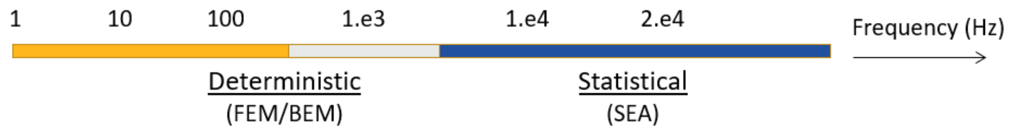
Features

- 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



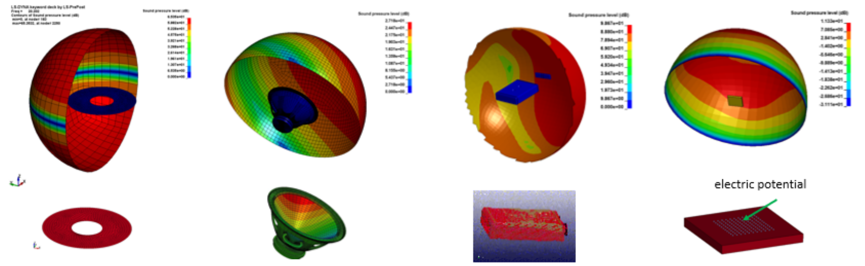


Spinning disc noise: coupling with rotor dynamics solver (Liping Li, Roger Grimes)

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)



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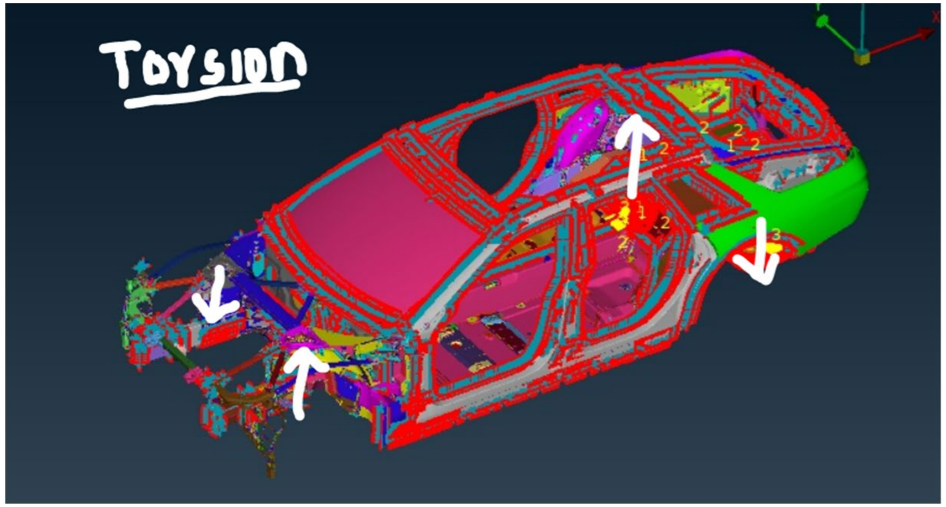
Recent updates

- FRF
- SSD
- Random vibration
- Response spectrum Analysis
- Fluid added mass
- Acoustic analysis by spectral element method
- Acoustic analysis by boundary element method
- d3max

FRF: overview of updates

- FRF analysis with IGA model (with Lam Nguyen)
- Added Torsion load

Card 1.a	N1	N1TYP	DOF1	VAD1	VID	FNMAX	MDMIN	MDMAX
Card 1.b	N1’	N1TYP’						
Card 2	DAMP	LCDAM	LCTYP	DMPMAS	DMPSTF			
Card 3	N2	N2TYP	DOF2	VAD2	RELATV			
Card 4	FMIN	FMAX	NFREQ	FSPACE	LCFREQ	RESTRT	OUTPUT	



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FRF: multiple load cases in one keyword

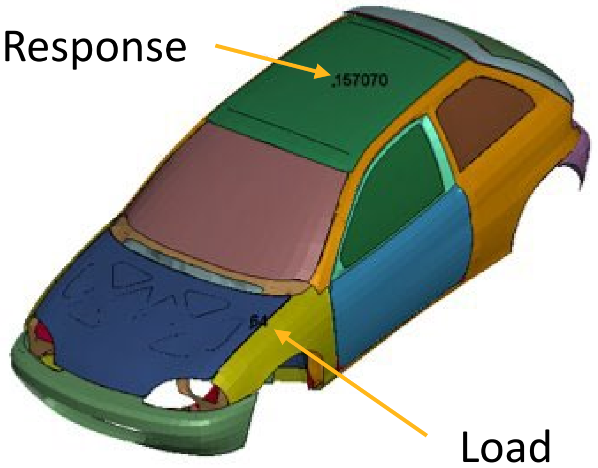
New approach

```
*FREQUENCY_DOMAIN_FRF_SUBCASE
           5                                         0
     0.001         5         1     0.000     0.000
  1.000000 400.00000       400         0         0
case1
       131         0         1         3         0
         1         1         3         1
case2
       132         0         3         3         0
         1         1         3         2
case3
       133         0         3         3         0
         1         1         2         3
case4
       134         0         3         3         0
         1         1         2         3
case5
       135         0         3         3         0
         1         1         2         3
```

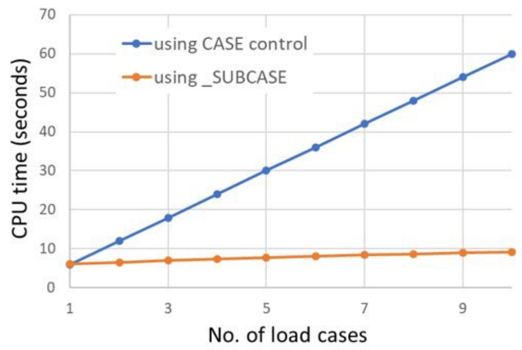
- **Benefits**
  - Save time for keyword input
  - Save time for MPP decomposition
  - Save time in reading eigenmodes
- **Results**
  - Subcase*.frf_amplitude
  - Subcase*.frf_angle

Old approach

```
*CASE_BEGIN_1
*FREQUENCY_DOMAIN_FRF
       131         0         1         3         0
     0.001         5         1     0.000     0.000
         1         1         3         1
  1.000000 400.00000       400         0         0
*CASE_END_1
*CASE_BEGIN_2
*FREQUENCY_DOMAIN_FRF
       132         0         3         3         0
     0.001         5         1     0.000     0.000
         1         1         3         1
  1.000000 400.00000       400         0         0
*CASE_END_2
*CASE_BEGIN_3
*FREQUENCY_DOMAIN_FRF
       133         0         3         3         0
     0.001         5         1     0.000     0.000
         1         1         3         1
  1.000000 400.00000       400         0         0
*CASE_END_3
*CASE_BEGIN_4
*FREQUENCY_DOMAIN_FRF
       134         0         3         3         0
     0.001         5         1     0.000     0.000
         1         1         3         1
  1.000000 400.00000       400         0         0
*CASE_END_4
*CASE_BEGIN_5
*FREQUENCY_DOMAIN_FRF
       135         0         3         3         0
     0.001         5         1     0.000     0.000
         1         1         3         1
  1.000000 400.00000       400         0         0
*CASE_END_5
```



CPU time for multiple load cases



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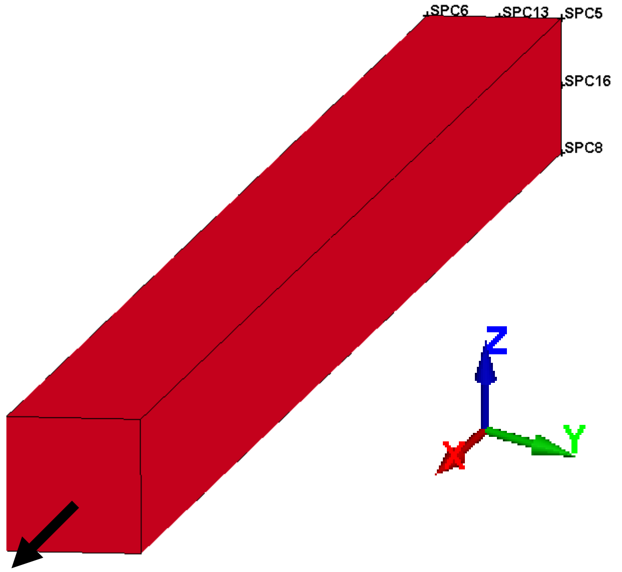
SSD: SECFORC_SSD

- Output from SSD
  - d3ssd
  - nodout_ssd
  - elout_ssd
  - nodfor_ssd
  - secforc_ssd

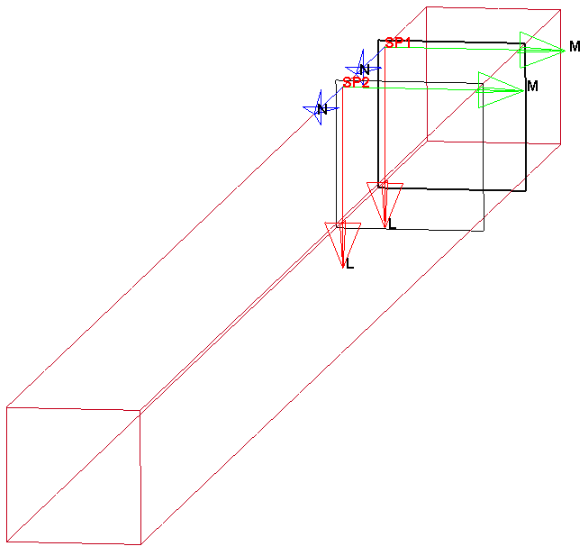
```
*DATABASE_FREQUENCY_ASCII_SECFORC_SSD
$#    fmin      fmax     nfreq    fspace    lcfreq
     1000.     2000.      1001
*DATABASE_CROSS_SECTION_PLANE_ID
       100
$#    psid       xct       yct       zct       xch       ych       zch
         0     10.00     0.000     5.000    100.00     0.000      5.00
$#    xhev      yhev      zhev      lenl      lenm        id     itype
     10.00      0.00      0.00     0.000     0.000
*DATABASE_CROSS_SECTION_PLANE_ID
       200
$#    psid       xct       yct       zct       xch       ych       zch
         0     20.00     0.000     5.000    100.00     0.000      5.00
$#    xhev      yhev      zhev      lenl      lenm        id     itype
     20.00      0.00      0.00     0.000     0.000
```




```
                   ls-dyna smp d DEV DEV_103136_34776c date 08/11/2023


line#1  section#     freq        x-force     y-force     z-force    (magnitude)
line#2                           x-moment    y-moment    z-moment   (magnitude)
line#3                           x-force     y-force     z-force    (angle)
line#4                           x-moment    y-moment    z-moment   (angle)
line#5  centroids                x           y           z            area
          1      1.00000E+03   1.3394E+02  3.9475E+01  8.1264E+00
                               3.1560E+00  9.5404E+01  4.4584E+02
                              -3.1355E-01 -2.8209E+01 -5.5691E+01
                              -2.2717E+01  1.2953E+02 -2.7726E+01
                               1.0000E+01  2.5654E+00  2.5890E+00  2.5000E+01

          2      1.00000E+03   1.2915E+02  3.5533E+01  7.4651E+00
                               3.8345E+00  2.0136E+01  5.7765E+01
                              -3.1188E-01 -2.8613E+01 -5.5212E+01
                              -2.8216E+01  1.5458E+02 -2.7850E+01
                               2.0000E+01  2.4900E+00  2.6118E+00  2.5000E+01
```



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SSD: including residual vectors

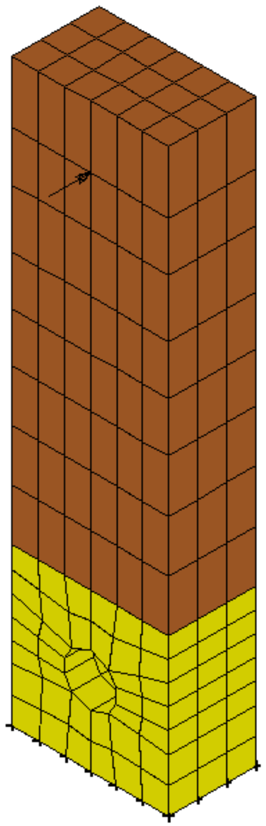
- Step 1: generate eigenmodes and residual vectors (Roger Grimes)

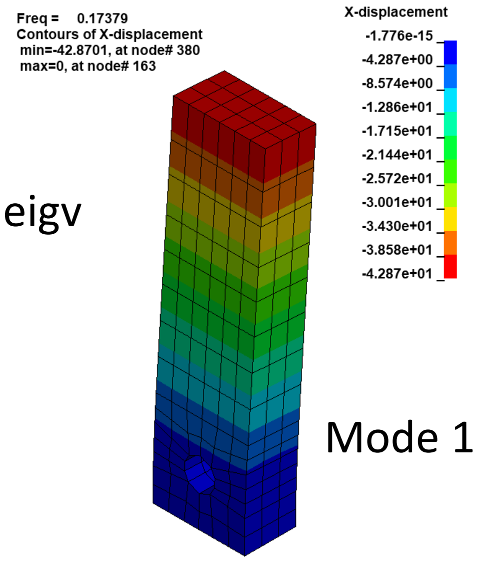
```
*CONTROL_IMPLICIT_GENERAL
$#  imflag       dt0    imform      nsbs       igs     cnstn      form    zero_v
         1  1.000000         2         1         1         0         0         0
*CONTROL_IMPLICIT_RESIDUAL_VECTOR
$#  resvec      neig     iparm
         1        50         1
*LOAD_NODE_POINT
$#     nid       dof      lcid        sf       cid        m1        m2        m3
       637         1     41011       1.0
*DEFINE_CURVE
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
     41011         0       0.0       0.0       0.0       0.0         0         0
$#                a1                  o1
                 0.0                 0.0
                 1.0                 1.0
*CONTROL_TERMINATION
$#  endtim    endcyc     dtmin    endeng    endmas
  1.000000         0     0.000     0.000     0.000
```

- Step 2: run SSD computation with eigenmodes and residual vectors

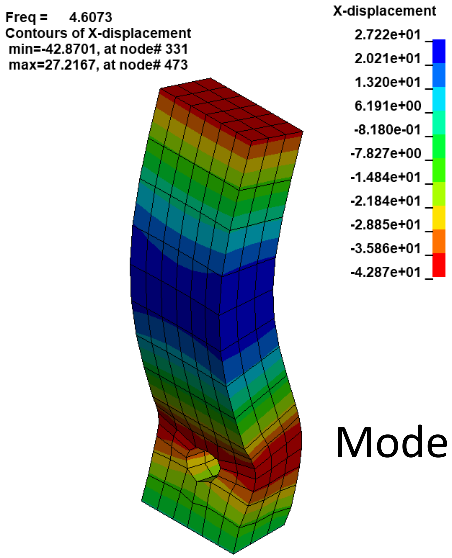
```
*FREQUENCY_DOMAIN_SSD
$#   mdmin     mdmax     fnmin     fnmax    restmd    restdp    lcflag
         1        50        0.   100000.         3         0         1
$#   rvmin     rvmax
         1         1
$#   dampf     lcdam     lctyp    dmpmas    dmpstf

$#                                                     nout     notyp      nova

$#     nid      ntyp       dof       vad       lc1       lc2       lc3       vid
       637         0         1         0       100       200
*FREQUENCY_DOMAIN_PATH
../residual_vector/d3eigv
*FREQUENCY_DOMAIN_PATH_RESIDUAL_VECTOR
../residual_vector/d3resvec
```

d3eigv

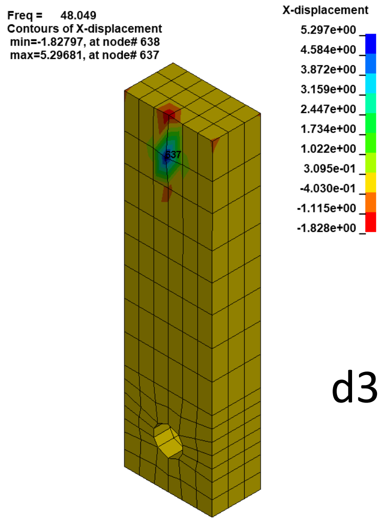




Mode 1



Mode 7



d3resvec

Total independent dofs: 1236

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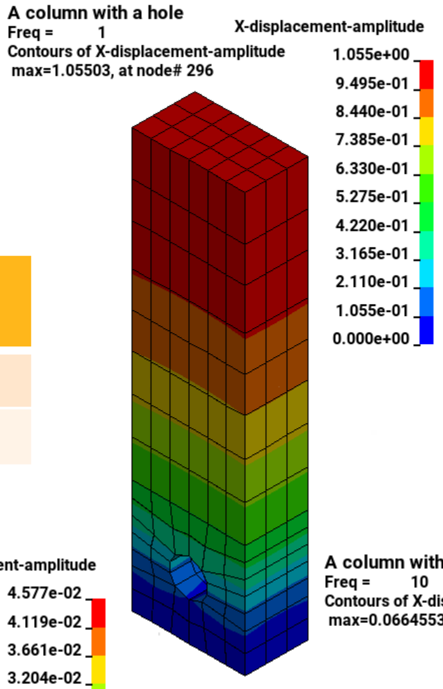
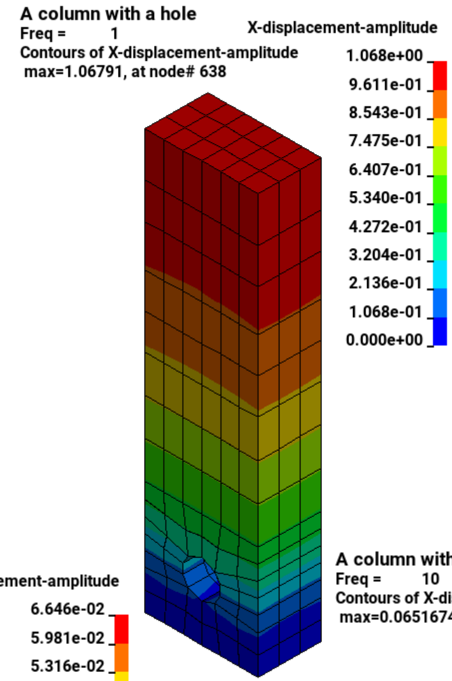
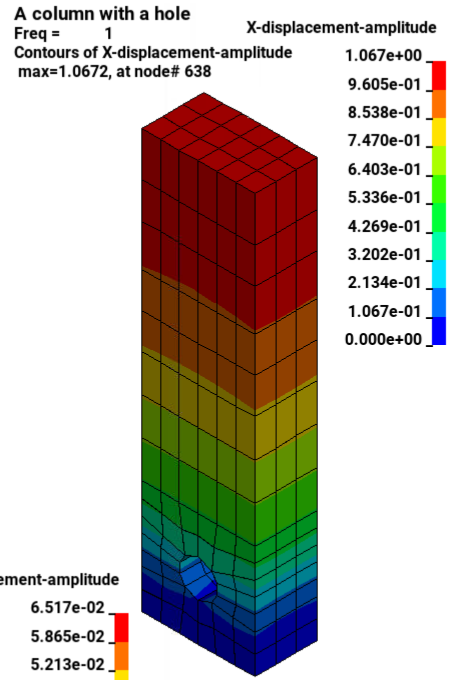
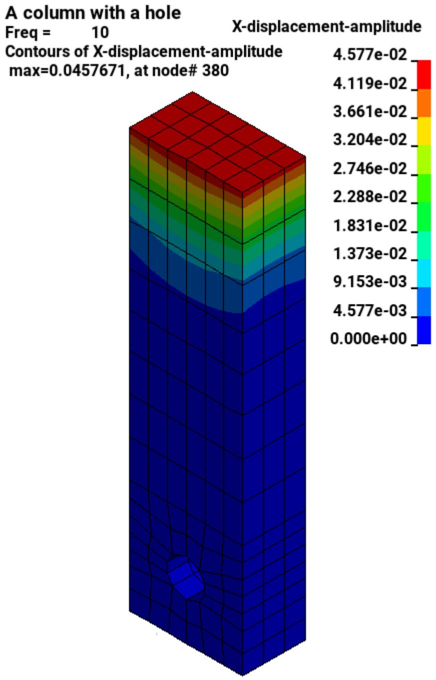
X-displacement (mm)

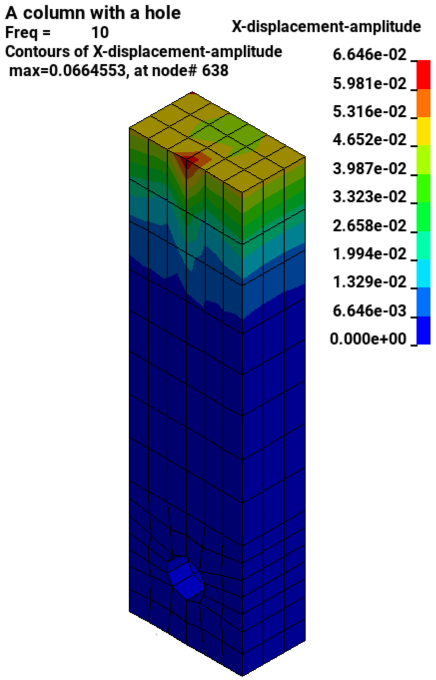
Freq (kHz)	50 modes	1236 modes	50 modes + residual vector
1	1.055	1.068	1.067
10	4.577e-2	6.646e-2	6.517e-2

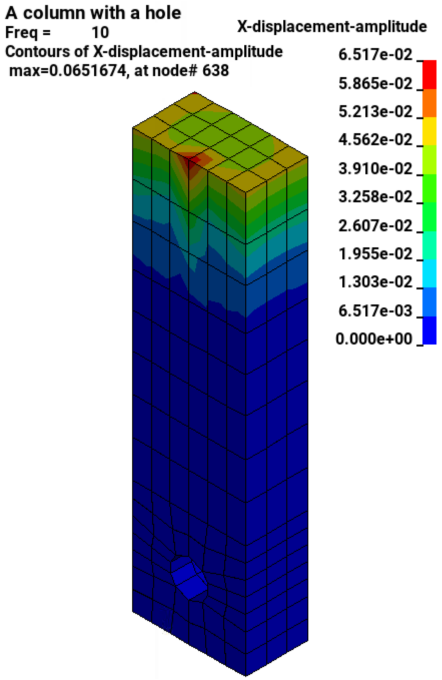












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Random vibration: combination of rms stress with prestress

- User would like to do failure analysis using stress in prestressed random vibration
- Total stress is sum of stress in random vibration and prestress
- User suggests to use 3*RMS + prestress
- New d3rms database
  - State 1: RMS response
  - State 2: 3*RMS + prestress
  - State 3: 3*RMS + |prestress|

```
*LOAD_SEGMENT_SET
$#     pid      lcid        sf
         1         1    1.e-5
*DEFINE_CURVE
$load curve for pressure loading
$#    lcid      sidr       sfa       sfo
         1         0
$#                a1                  o1
                 0.0                 0.0
                 1.0                 1.0
```

```
*FREQUENCY_DOMAIN_RANDOM_VIBRATION
$#   mdmin     mdmax     fnmin     fnmax    restrt              restrm
         1        15        0.    90000.
$#   dampf     lcdam     lctyp    dmpmas    dmpstf    dmptyp
      0.03
$#  vaflag    method      unit      umlt     vapsd     varms     napsd     ncpsd
         1         1         0                   1         1
$#   ldtyp    ipanelu   ipanelv    temper              dsflag

$#     sid     stype       dof     ldpsd     ldvel     ldflw     ldspn       cid
                             3      2001
*DATABASE_FREQUENCY_BINARY_D3RMS
$#  binary        sf
         3       3.0
$#   state                        filename
         2                        ../pressure/d3plot
```

User defined scale factor
Default: 3.0

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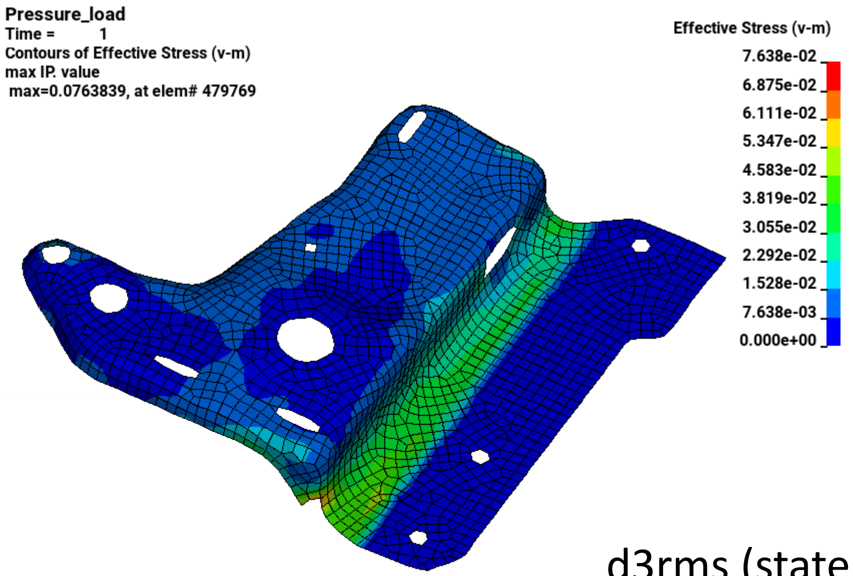
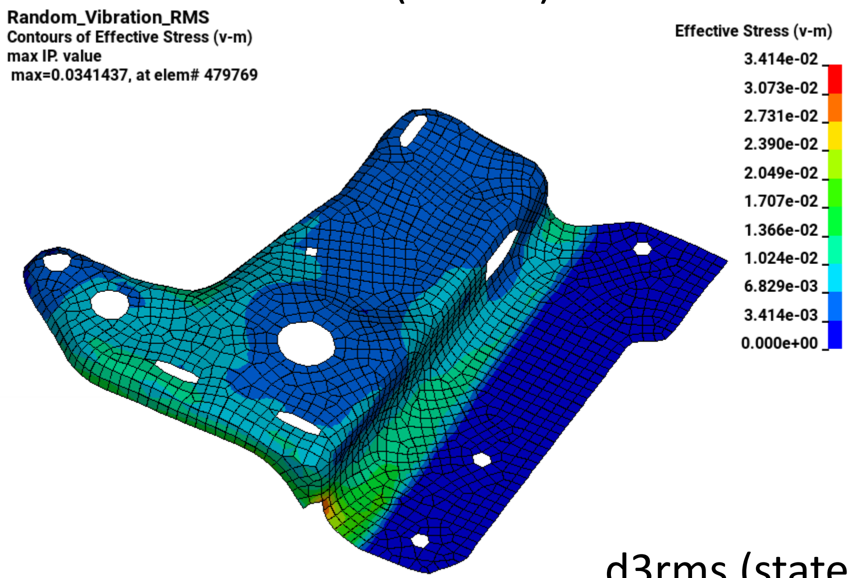
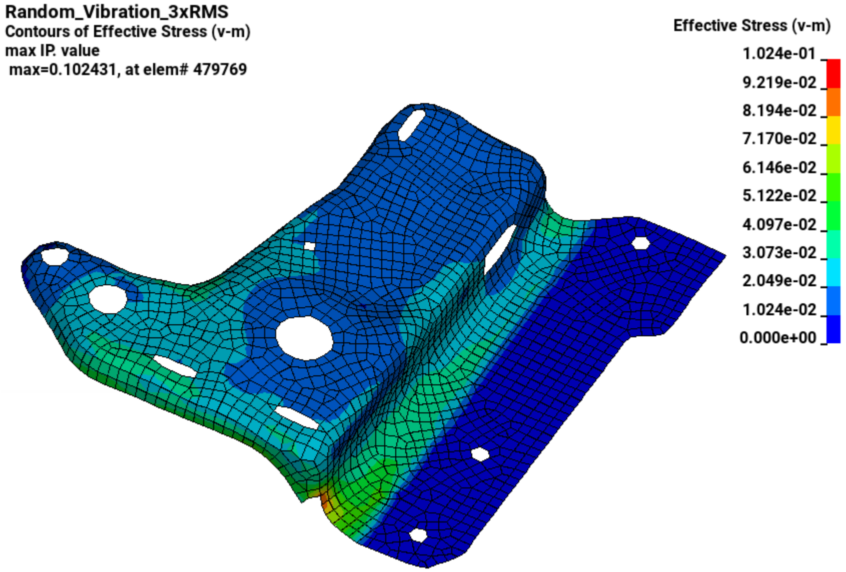
d3plot (2nd state)



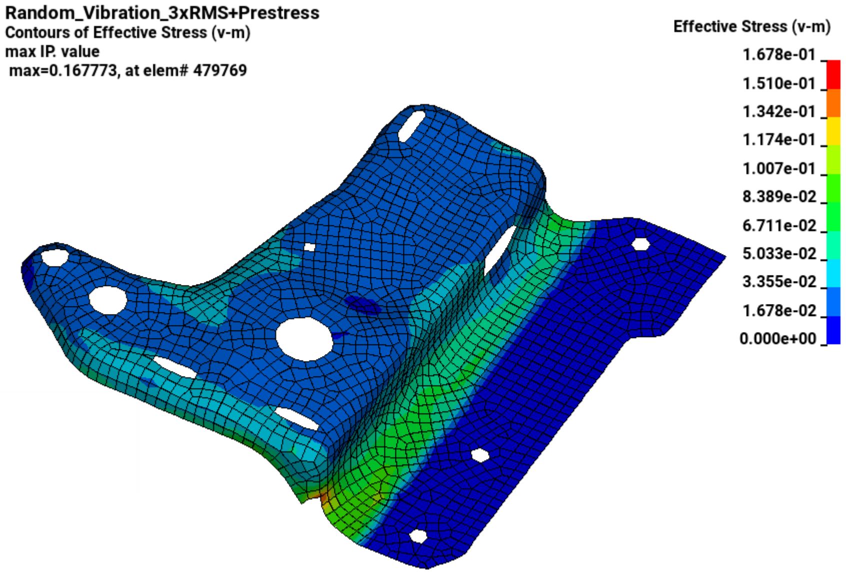
d3rms (state 1)



d3rms (state 1) x3



d3rms (state 2)



- Static pressure 10^4 Pa
- 2.0 G^2/Hz z-directional ground acceleration
- Material yield strength: 1.50e-01 GPa

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Response spectrum analysis: missing mass correction

- In general, a mode superposition using a limited number of modes will miss some mass.
- For response spectrum analysis, static correction can be made by adding static load response for the missing mass.
- Missing mass load is provided by ZPA-∑(mode load).

```
*LOAD_BODY_Y
       101
*DEFINE_CURVE
       101
               0.000           1.000000000
               1.000           1.000000000
*CONTROL_IMPLICIT_SOLVER
                     1
*CONTROL_IMPLICIT_DYNAMICS
         0
```

```
*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM_MISSING_MASS_CORRECTION
$#   mdmin     mdmax     fnmin     fnmax    restrt     mcomb    relatv
         1       200        0.      100.
$#     zpa      filename
       2.0    case1.d3plot
$#   dampf    lcdamp     ldtyp    dmpmas    dmpstf
      .001
$#   lctyp         dof    lc/tbid       sf       vid      lnid     lntyp    inflag
$        1         1     27000        0.
         1         2     27000        0.
$        1         3     27000        0.
*DATABASE_FREQUENCY_BINARY_D3SPCM
$#  binary
         1
```


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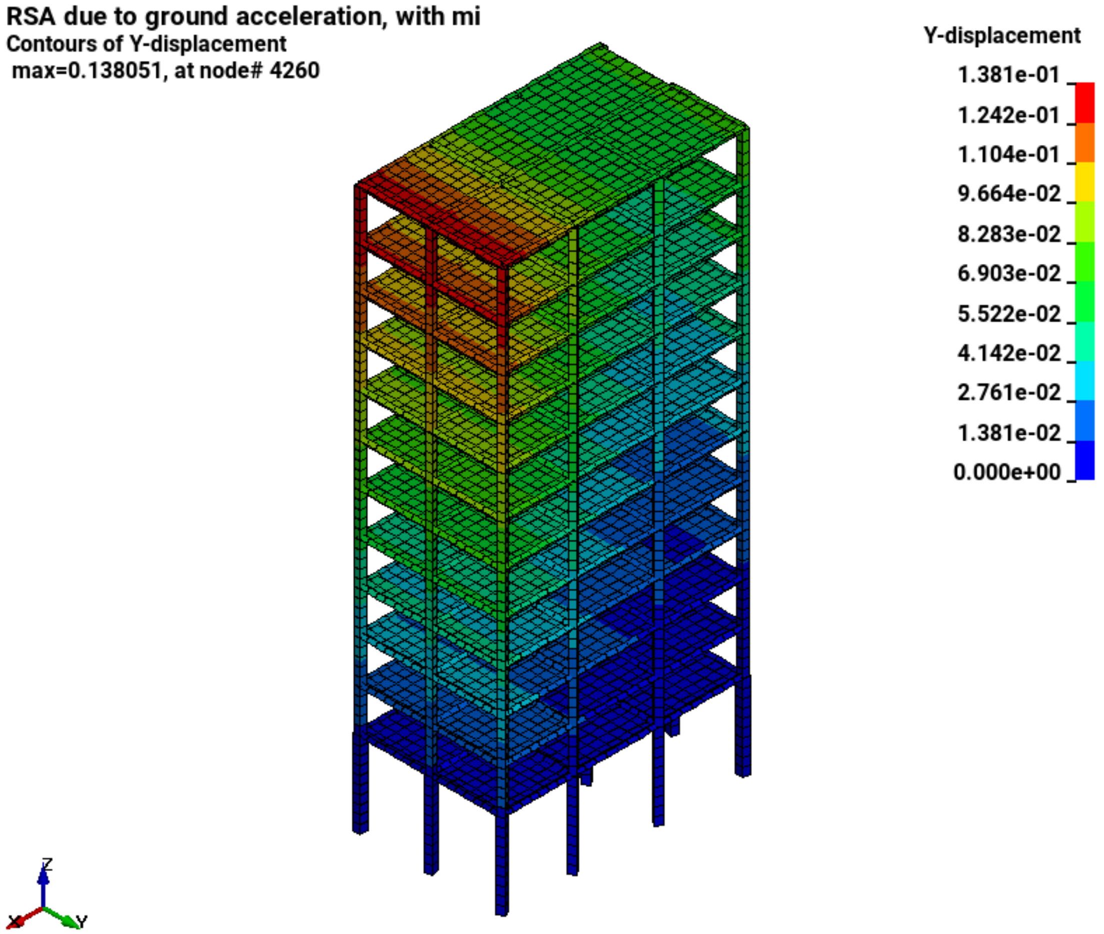
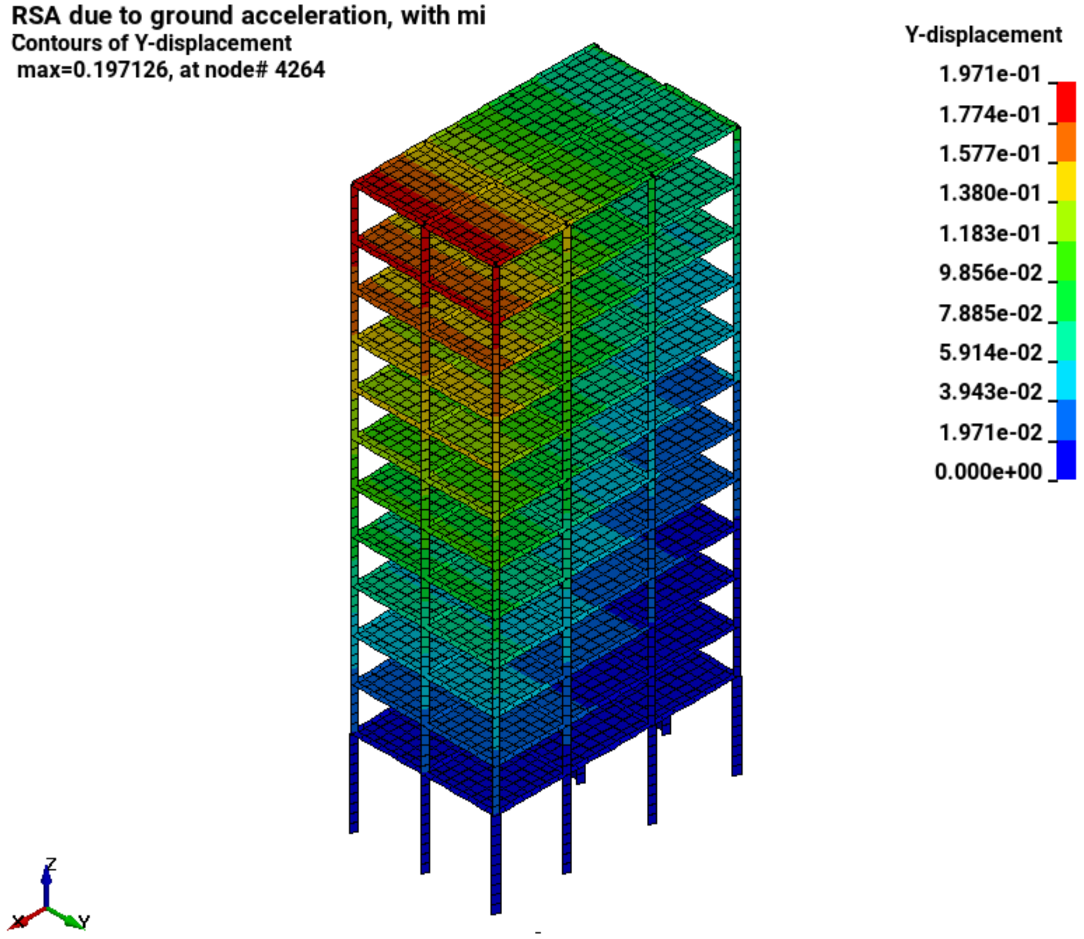
Without missing mass correction



With missing mass correction



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Fluid added mass: related Keywords and their usage

Keywords	Description
*BOUNDARY_FLUIDM	Request the calculation of the external, fluid boundary mass on a structural surface in an inviscid, incompressible fluid.
*BOUNDARY_FLUIDM_FREE_SURFACE	Includes the effects of a flat, arbitrarily oriented free surface in the calculation of the *BOUNDARY_FLUIDM mass matrix
*BOUNDARY_FLUIDM_BOTTOM	Includes the effects of a flat, arbitrarily oriented bottom in the calculation of the *BOUNDARY_FLUIDM mass matrix. Due to proximity effect, when nearby, a bottom will increase the added mass experienced by a submerged structure.
*CONTROL_IMPLICIT_EIGENVALUE	Eigmth = 102 for LOBPCG eigensolver.
*FREQUENCY_DOMAIN_	Various frequency domain vibration analysis using eigensolutions

Note:
Keyword *BOUNDARY_FLUIDM_BOTTOM can be combined with *BOUNDARY_FLUIDM_FREE_SURFACE in very shallow conditions.

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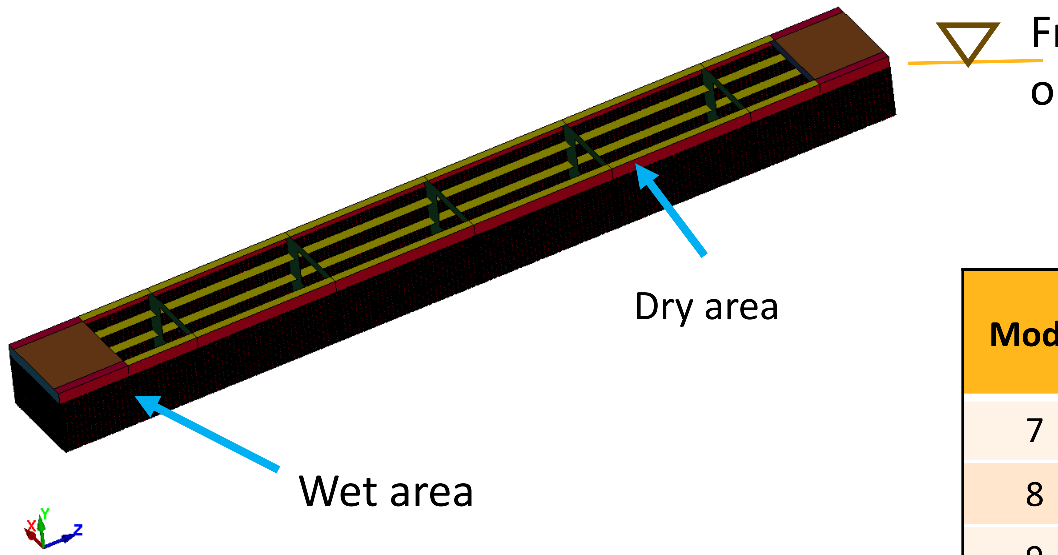
Example: a stiffened, floating box

- In-air and in-fluid modal tests were conducted by Cambridge Acoustical Associates in 1998. The stiffened box is 32 ft long and 1.17 ft wide with a draft of 1.96 ft.



Free surface: 24.03 inch from origin of global coordinates

Natural frequencies in-air and in-fluid

Mode	Description	In-Air (Hz)		In-Fluid (Hz)	
		Experiment	LS-DYNA	Experiment	LS-DYNA
7	Torsion	16.1	15.6	14.9	14.8
8	Lateral bending	29.0	29.5	25.6	25.5
9	Vertical bending	38.3	37.1	29.5	28.5
10	Lateral bending	62.6	62.9	55.0	54.0
11	Vertical bending	94.2	91.0	68.5	65.8

Note: modes 1-6 are rigid body modes

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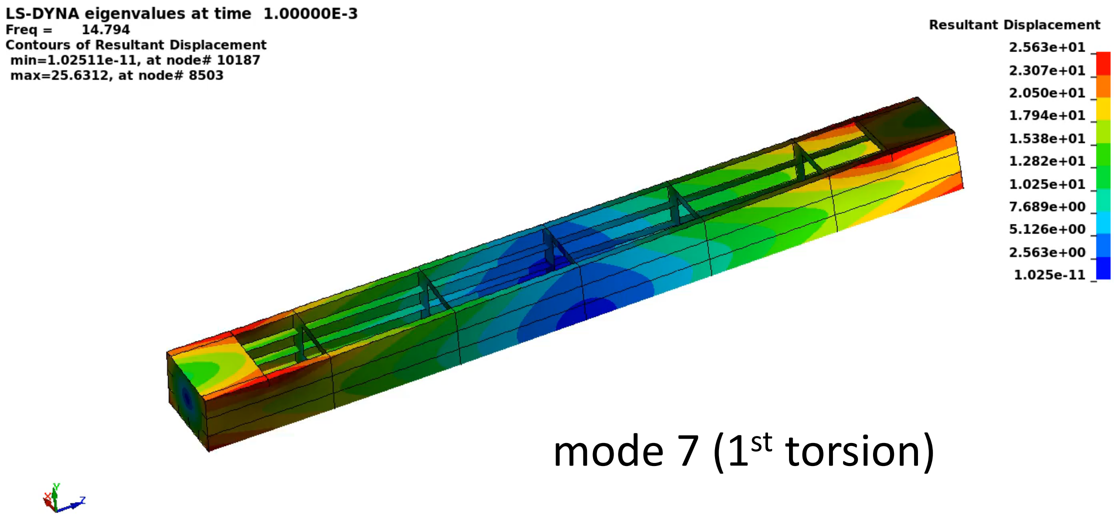
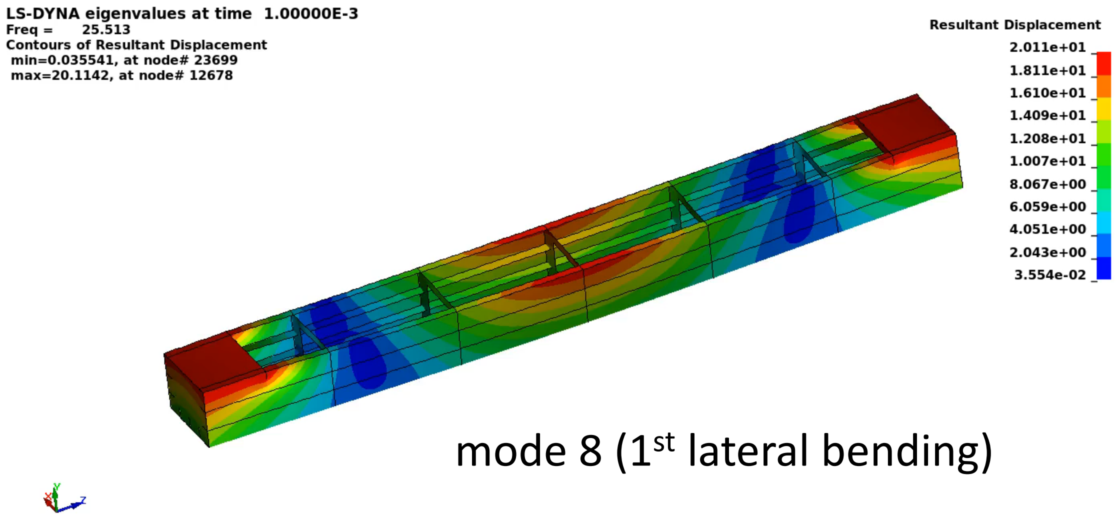
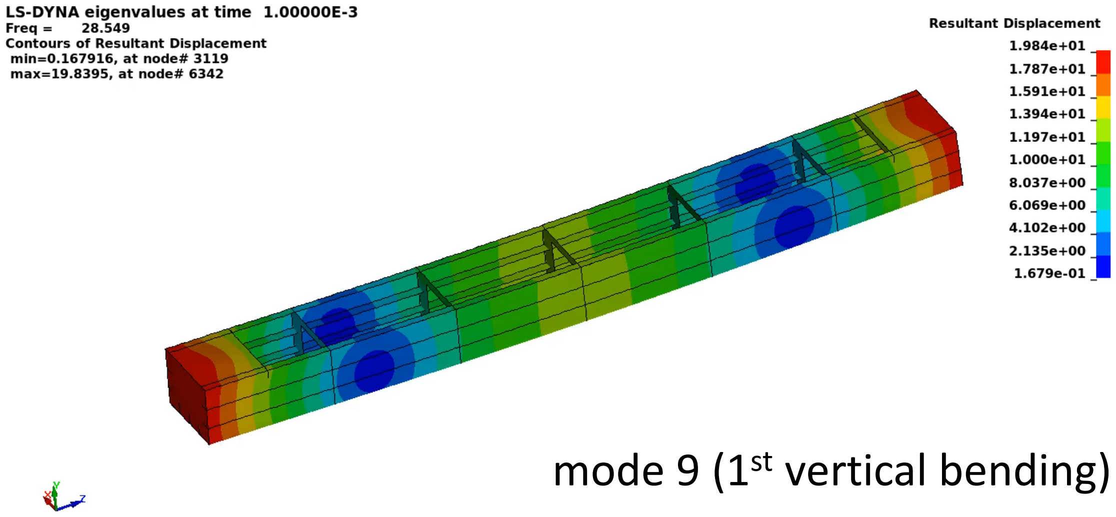
In-fluid eigenmodes for the floating box



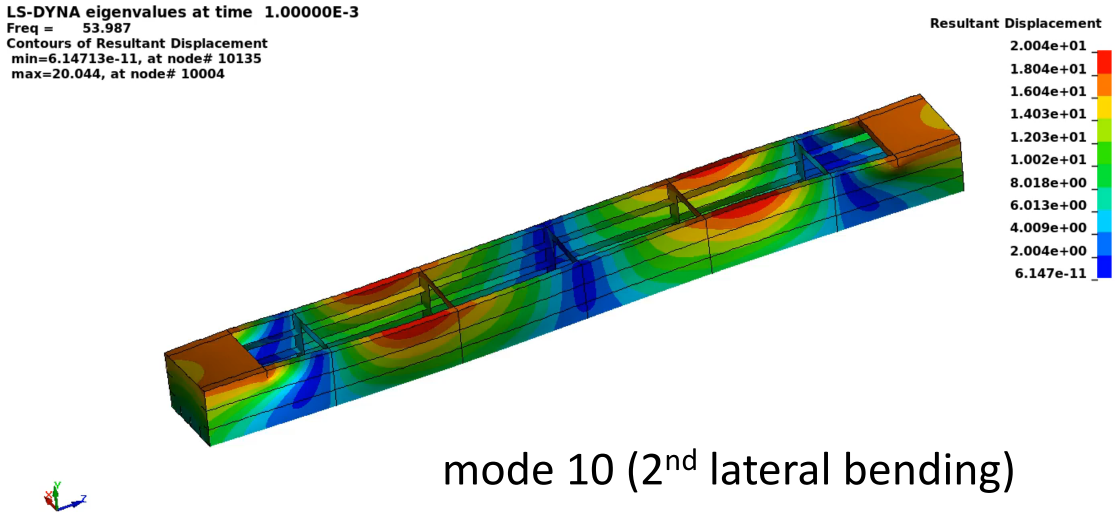
mode 7 (1^{st} torsion)



mode 8 (1^{st} lateral bending)



mode 9 (1^{st} vertical bending)



mode 10 (2^{nd} lateral bending)

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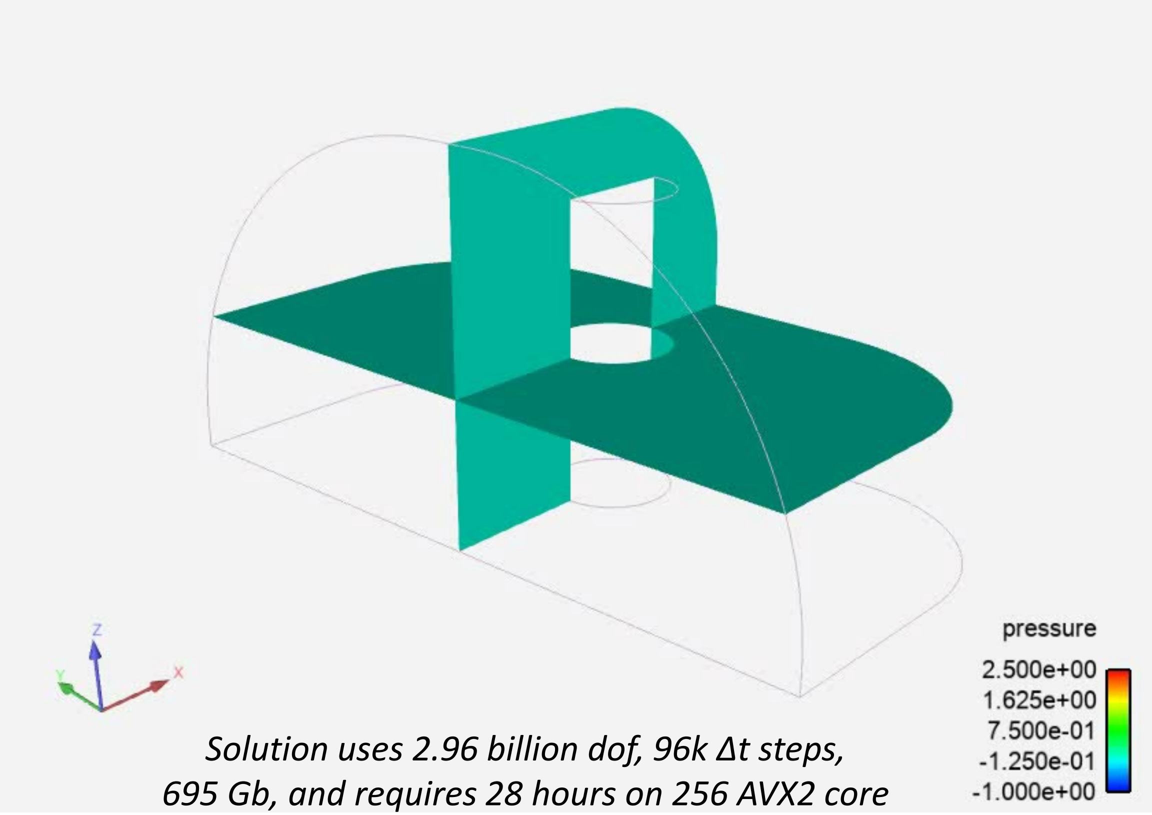
Acoustics by spectral element method

- Reworked transient MPP implementation to overcome unanticipated 2.1 billion barriers.
- Added support for ENSIGHT visualization of LS-DYNA transient spectral element solutions.
- Demos and support (→) provided for ACE, Channel Partners,…
- Study of SE methods for extension to tetrahedra, pentahedra, and pyramids so we can use hex-coring for mesh generation

Steel Pole at 30 cm, Ground Porous Concrete,
50 kHz Pulse, Dissipation of 1.3 dB / 30 cm



Solution uses 2.96 billion dof, 96k Δt steps,
695 Gb, and requires 28 hours on 256 AVX2 core

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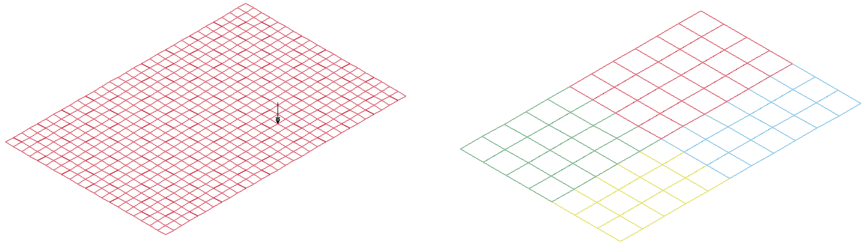
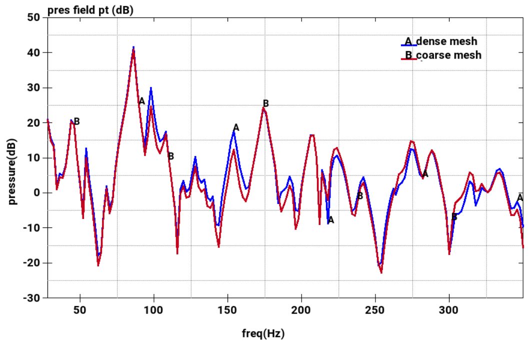
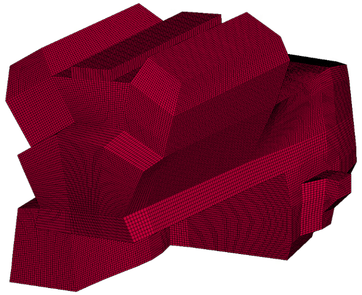
Acoustics by BEM: overview of updates

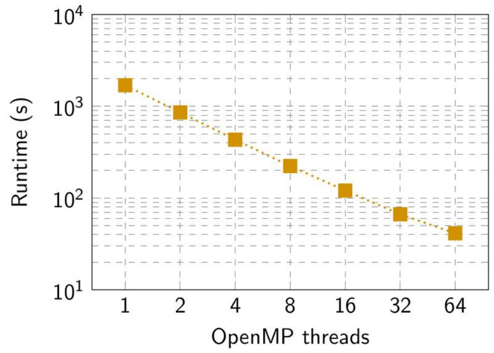


- New boundary conditions
  - acoustic absorption coefficient boundary conditions
  - Symmetry (rigid wall) boundary condition
- An option to get results for new field points quickly
- SMP and fast matrix assembly by skeletonized interpolation (Francois-Henry Rouet)
- BEM run based on velocity from a different mesh
  “lsdyna i= input.k bem=vel_coarse lbem=vel_dense”




```
*FREQUENCY_DOMAIN_ACOUSTIC_BEM
$#        ro         c      fmin      fmax     nfreq    dt_out   t_start      pref
  1.210000 340.00000 28.000000 350.00000       162     0.001     0.000 2.0000E-5
$# nsidext   typeext   nsidint   typeint    fftwin     trslt   ipfile    iunits
         1         1         0         0         4
$#  method     maxit       res       ndd     tollr    tolfct     ibdim       npg
         2      1000 1.0000E-6         2
$#    ssid    sstype      norm  bem_type   restart     iedge      noel    nfrup
         1         2         0         0         4
```





Engine block model, 78k dof. Speed-up of 41 out of 64 using OpenMP

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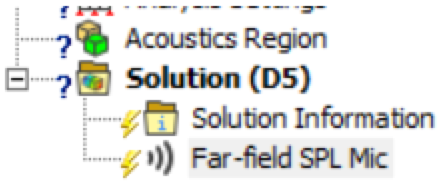
Acoustics by BEM: a quick restart to get more results

Suggestion from Ansys WB team (Laurent Sabatier):

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.



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


```
*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)
```

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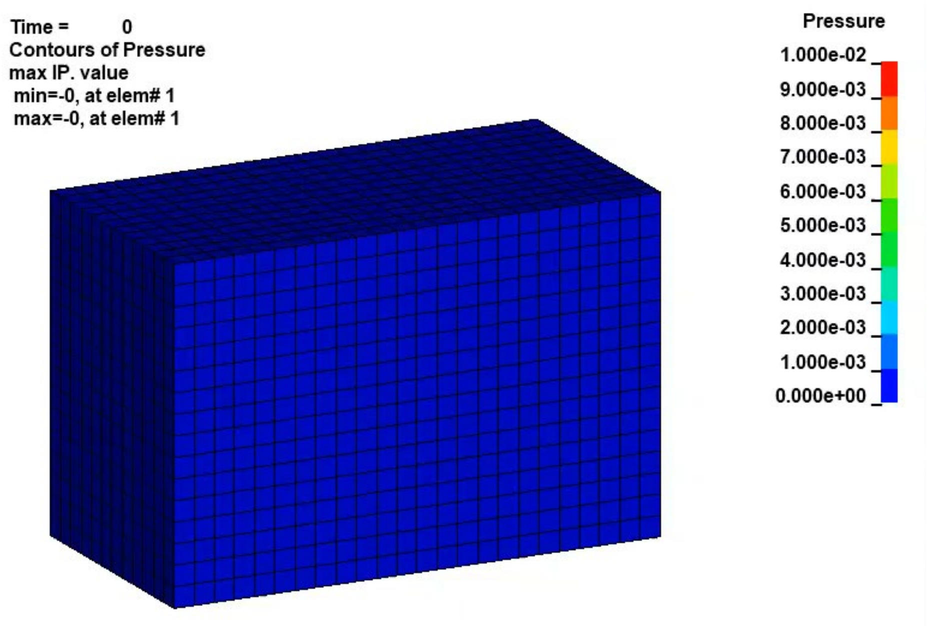
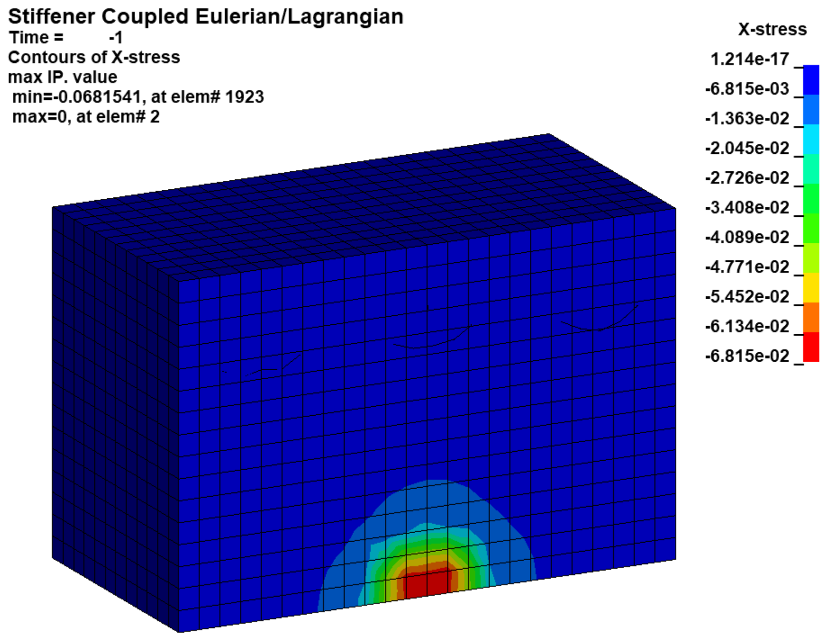
d3max

- ALE results are supported (Hao Chen, Nicolas Aquelet, Ian Do, and Nikolay Mladenov)
- Small restart and simple restart are supported
- Thick shell elements are supported





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Conclusion

Summary

- A series of NVH solvers have been developed in LS-DYNA
  - Focused on application in automotive industry, where LS-DYNA has been widely used.
  - Allow users to run NVH analysis with minor changes to their existing LS-DYNA models (crash, etc.)
  - “One button” Crash model to NVH model conversion is on the way (Philip Ho)
  - Aiming at multi-disciplinary design optimization for vehicles, with other modules in LS-DYNA.
  - Seamless coupling / integration with other solvers in LS-DYNA (e.g. metal forming)
- Is being integrated to Ansys Mechanical environment
- Tested and validated by many users (still, this is an on-going effort, and we need your help ☺)
- Training, tutorials and samples are available (ALH, or local)
- More features to be added (adaptive remeshing for boundary elements, nonlinear acoustics, etc.)
- Looking forward to feedback and suggestions from customers like you ☺

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