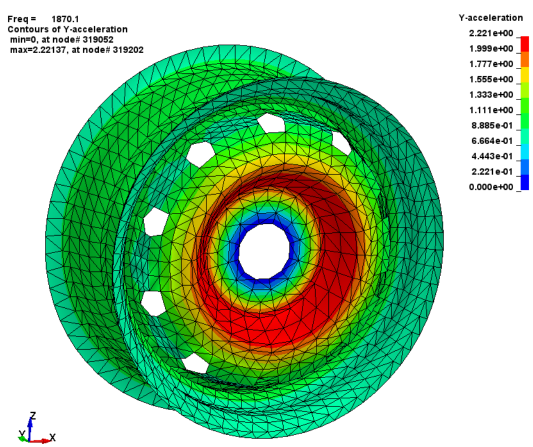
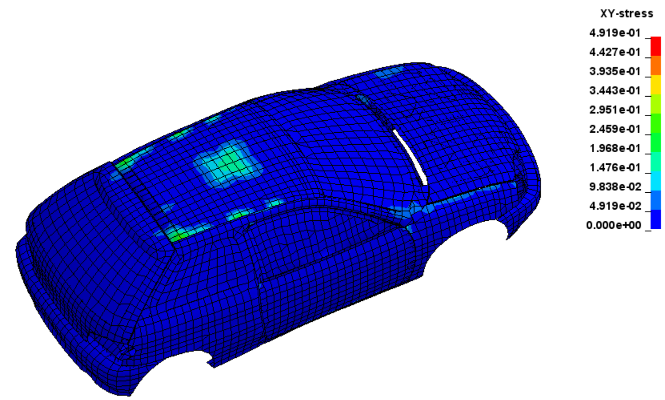
Direct Steady State Dynamic (SSD) Analysis with LS-DYNA®





Yun Huang, Zhe Cui, Francois-Henry Rouet, Cleve Ashcraft, Roger Grimes

Livermore Software Technology Corporation

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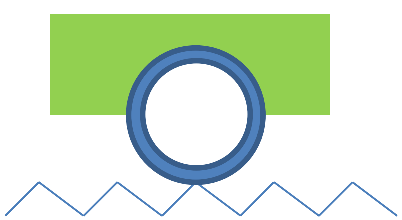
Current SSD solver based on modes

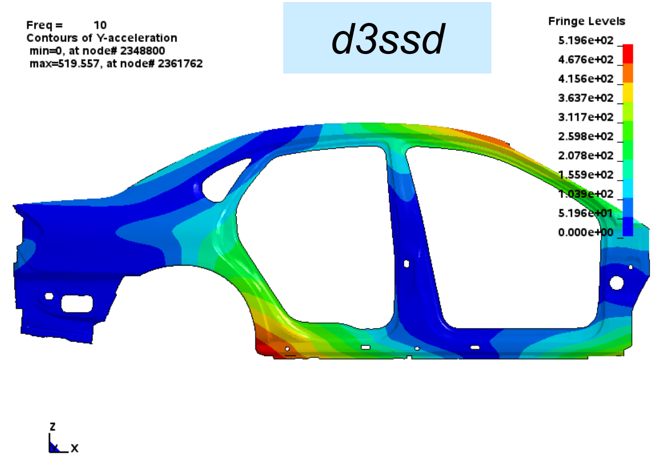
***FREQUENCY_DOMAIN_SSD**

- Harmonic excitation is often encountered in engineering systems. It is commonly produced by the unbalance in rotating machinery.
- The load may also come from periodic load, e.g. in fatigue test.
- The excitation may also come from uneven base, e.g. the force on tires running on a zig-zag road (rough road shake test)

$$\boxed{F\,(t) = F_0 \sin(\omega t + \phi)}$$

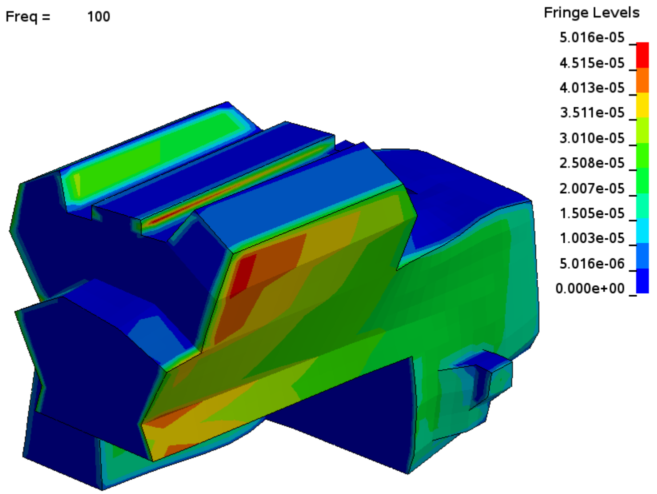


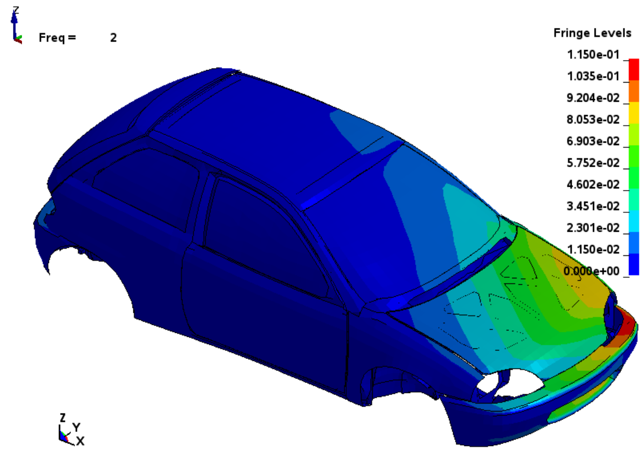
Typical harmonic excitation



Acceleration of auto side frame under harmonic excitation

*FREQUENCY_DOMAIN_SSD_*{ERP}**



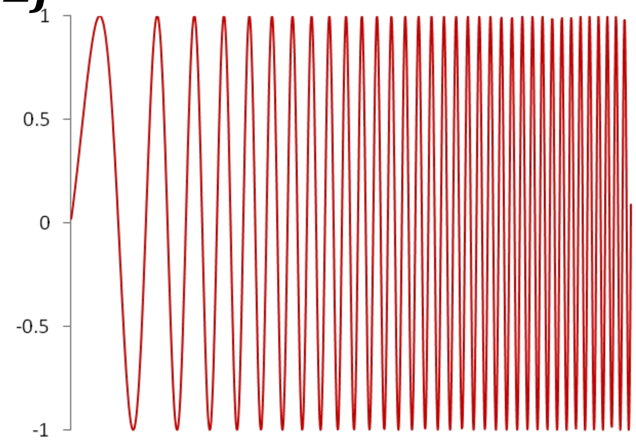


Calculation of ERP (Equivalent Radiated Power) is a simple and fast way to characterize the structure borne noise. It gives user a good look at how panels contribute to total noise radiation. It is a valuable tool in early phase of product development.

ERP calculation results are saved in

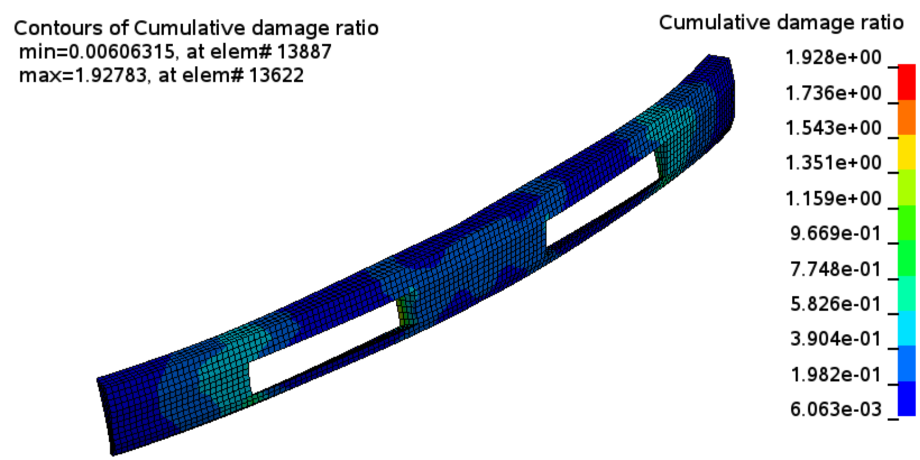
- *Binary database*
  - ✓ *d3erp*
- *ASCII xyplot files*
  - ✓ *ERP_abs*
  - ✓ *ERP_dB*

*FREQUENCY_DOMAIN_SSD_*{FATIGUE}**



- Calculate fatigue life of structures under steady state vibration (e.g. sine sweep)
- Based on S-N fatigue curve
- Based on Miner's Rule of Cumulative Damage Ratio
- Rainflow counting algorithm for each frequency for one period

$$R = \sum_i \frac{n_i}{N_i}$$



Direct SSD Solver: introduction

FREQUENCY_DOMAIN_SSD_*{DIRECT}

- Direct SSD solves the dynamic system in physical space, not in modal space
  - No expensive eigenvalue analysis.
  - No error due to mode truncation.
  - Based on LS-DYNA's Constrained Linear System Solver (LSCLSS).
- Frequency-dependent material properties can be considered, using the keyword ***MAT_ADD_PROPERTY_DEPENDENCE**
  - It defines how a property of a material model changes with frequency.
  - Stiffness and damping matrices can be updated at each frequency.

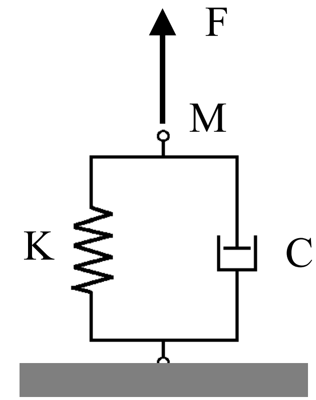
```
*FREQUENCY_DOMAIN_SSD_DIRECT_FREQUENCY_DEPENDENT
$#   mdmin     mdmax     fnmin     fnmax    restmd    restdp    lcflag    relatv

$#   dampf     lcdam     lctyp    dmpmas    dmpstf    dmpflg
      0.01
$#                      memory      nerp    strtyp      nout     notyp      nova

$#     nid      ntyp       dof       vad       lc1       lc2    lcflag       vid
       131         0         3         0       100       200
       651         0         3         0       101       201
*MAT_ADD_PROPERTY_DEPENDENCE_FREQ
$#     mid      prop      lcid
         1         e       300
*MAT_ELASTIC
$#     mid        ro         e        pr        da        db         k
         1  7.87E+03  2.07E+11  .292E+00
*DEFINE_CURVE
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
       300
$#                a1                  o1
                 0.0            2.00E+11
              1001.0            3.00E+11
```

LS-DYNA's Constrained Linear System Solvers

$$\mathbf{M}a + \mathbf{C}v + \mathbf{K}u = F(t)$$

$$\left(-\omega^2\mathbf{M} + i\,\omega\mathbf{C} + \mathbf{K}\right)u = F(\omega)$$

$$Au = F$$



Minimize $u^T Au - u^T F$ (Energy function)

Subject to $Cu = g$ (Linear Constraints)

A: Stiffness matrix
C: Constraint matrix
u: Displacement vector
F: Force vector

By forming the Lagrangian and finding a saddle point, this is equivalent to the KKT system:

$$\begin{bmatrix} A & C^T \\ C & 0 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} b \\ d \end{bmatrix}$$

Work flow chart

LCPACK analyzes the constraint matrix and forms the reduced system (independent dofs)

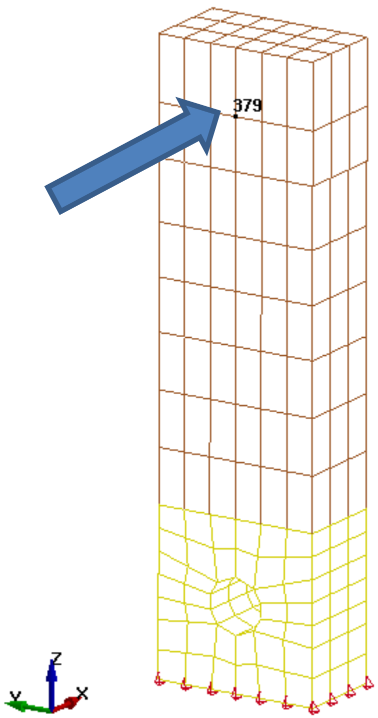
The reduced system is solved using the direct solver (mf2) or our in-house implementations of Conjugate Gradient or GMRES.

LCPACK expands the reduced solutions to all dofs.

Compute stress / strain if requested

Output (d3ssd)

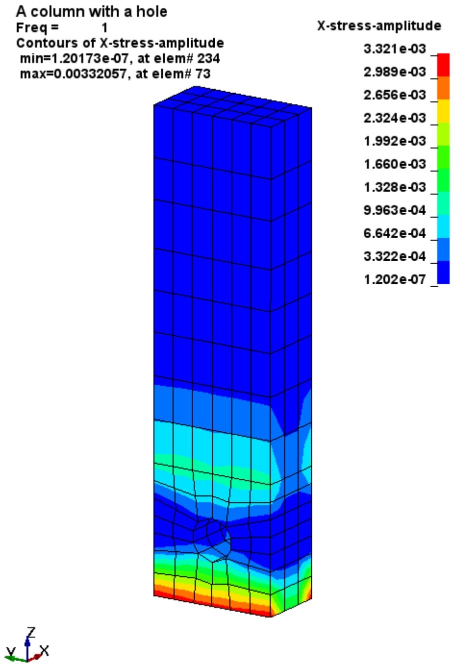
A benchmark example for cross-validation [(input deck)]

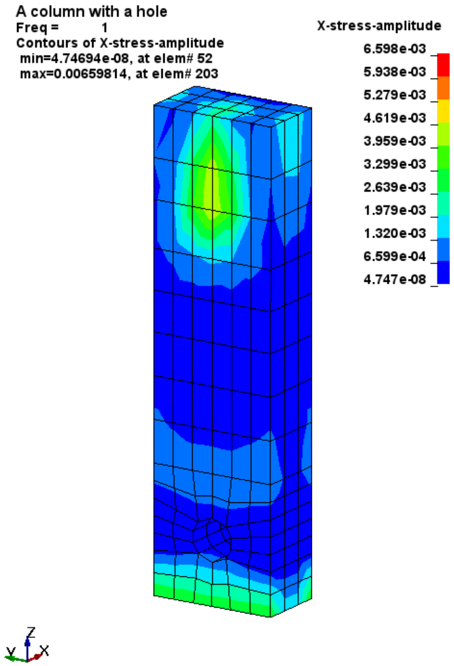


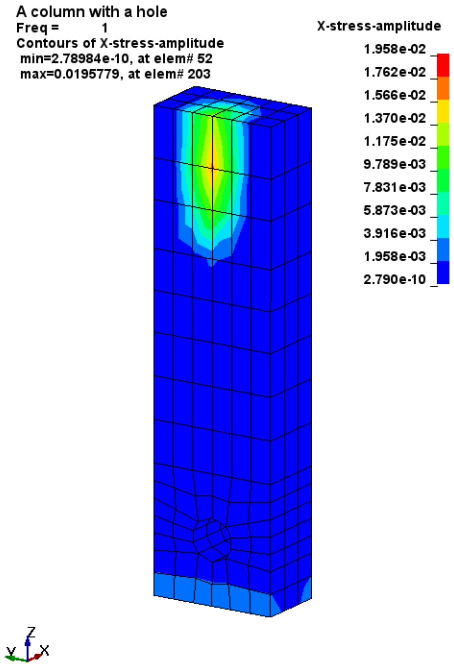
- Harmonic nodal force is applied at node 379, for 1-10 kHz.
- Total number of nodes: 440
- The base (28 nodes) is constrained in all dof.
- The total number of modes: 3 x 412 = 1236

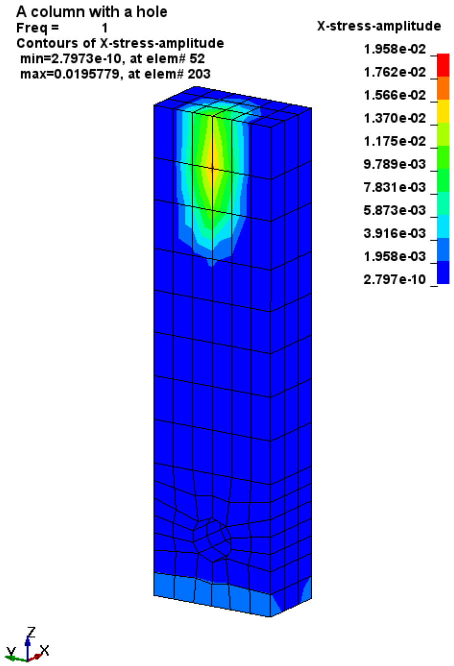
A conservative rule of thumb is to extract enough modes to cover 1.5 times the maximum frequency in the excitation.
But ?

σ_{xx} at 1 kHz (d3ssd)

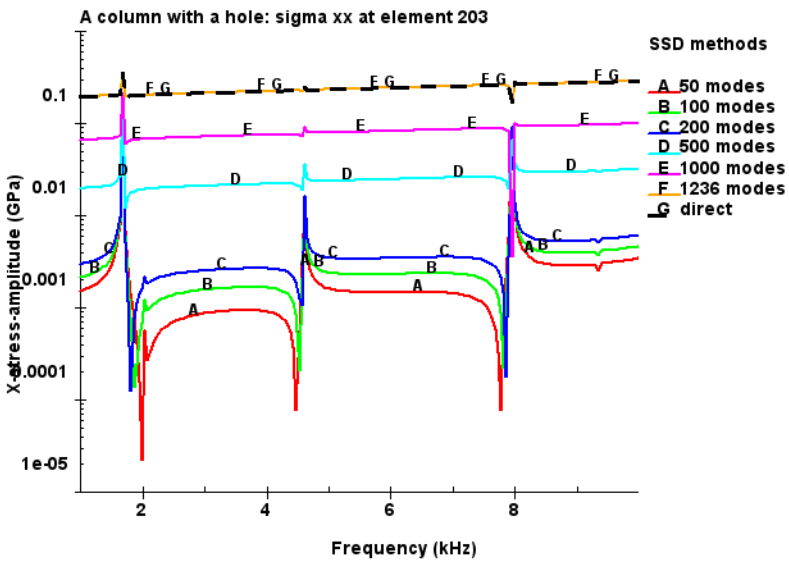


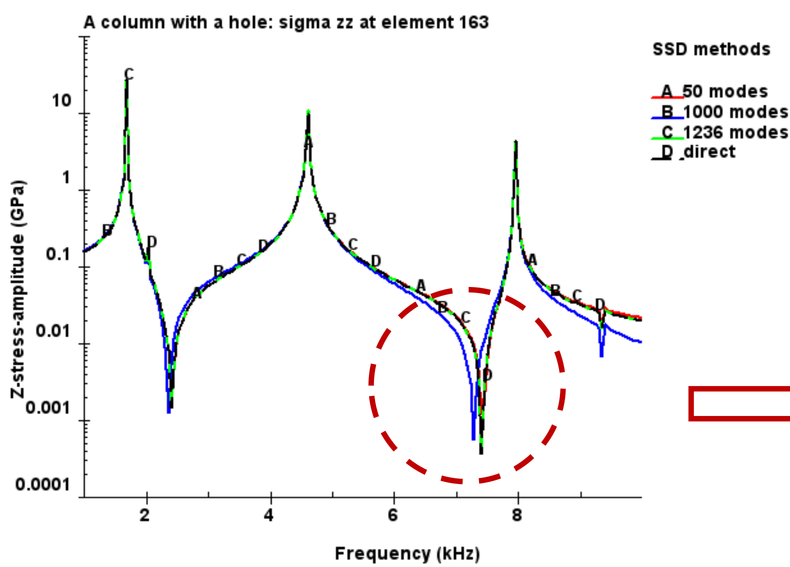






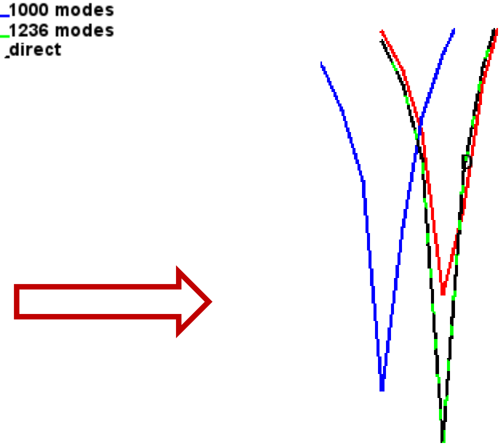
50 modes	*1000 modes*	*1236 modes*	*Direct SSD*
fmax = 19.875 kHz	*fmax = 81.396 kHz*	*fmax = 180.267 kHz*	



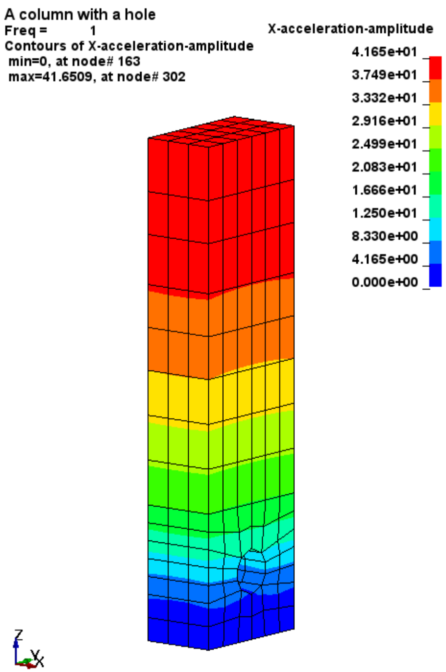


σ_{xx} *at the loading element by mode-based SSD converges to the value by direct SSD, when more and more modes are involved.*

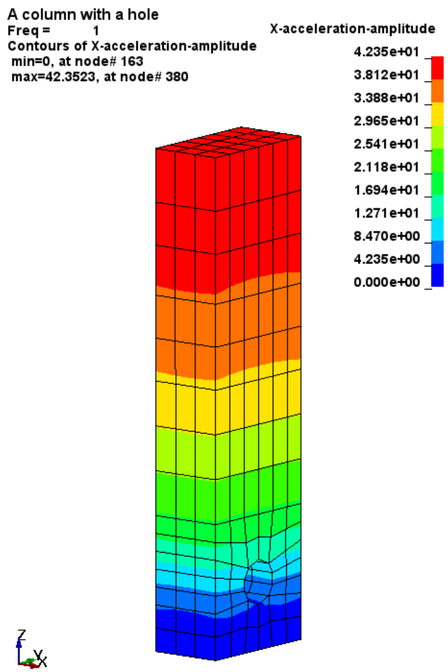
For other stresses, there is always good match between mode-based SSD and direct SSD.



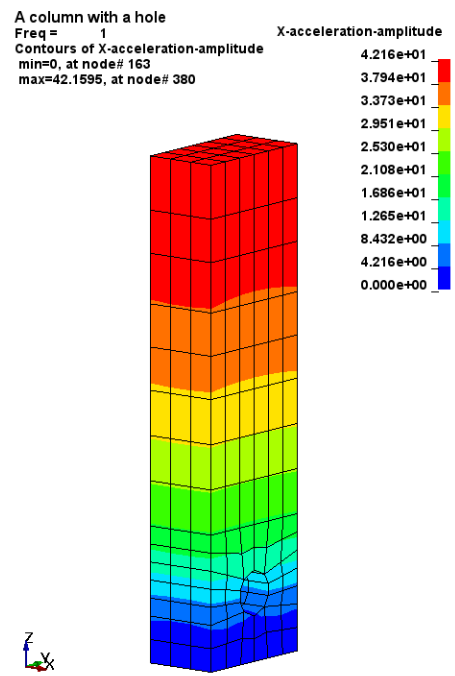
X-acceleration at 1 kHz (d3ssd)



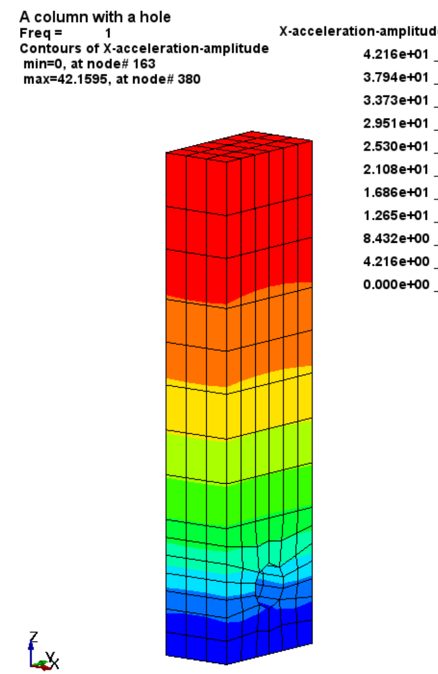
50 modes
fmax = 19.875 kHz



1000 modes
fmax = 81.396 kHz

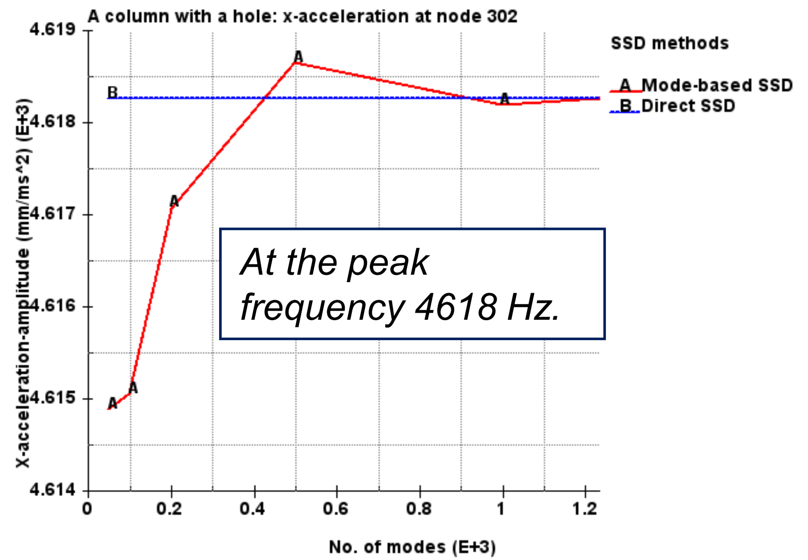


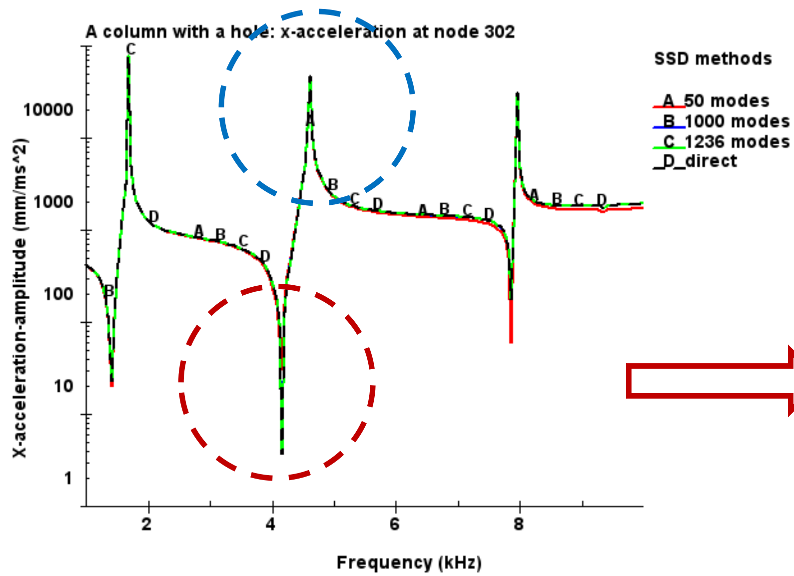
1236 modes
fmax = 180.267 kHz

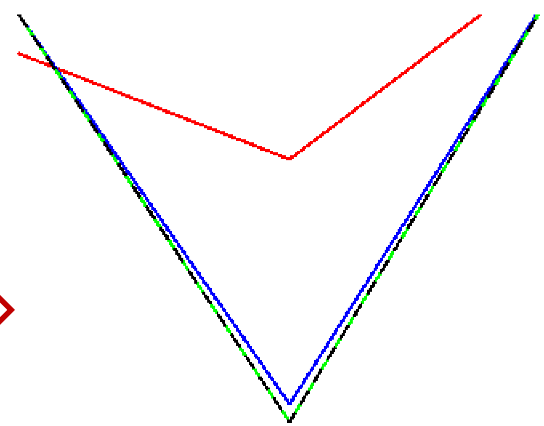


Direct SSD

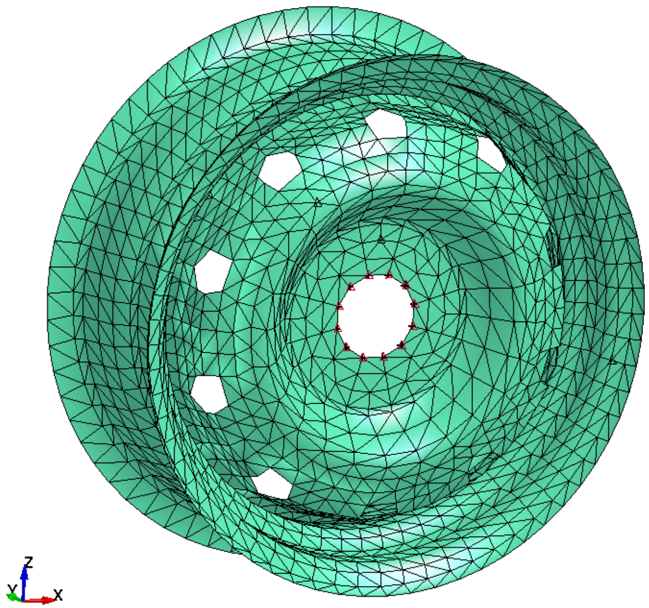
Acceleration by mode-based SSD converges to the value given by direct SSD, when more and more modes are involved.







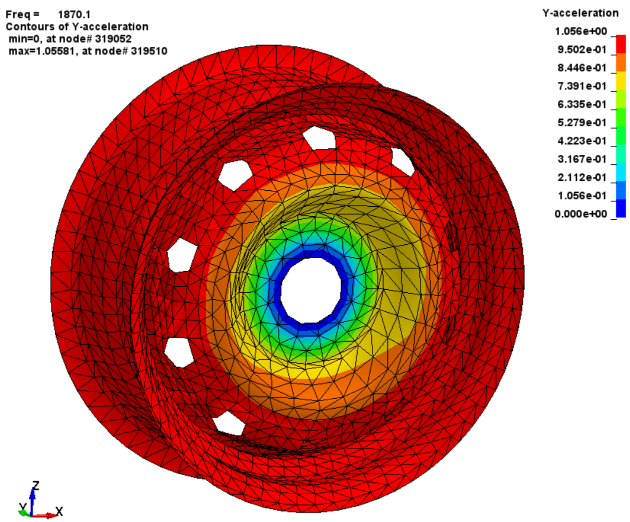
Examples: *2) shells*



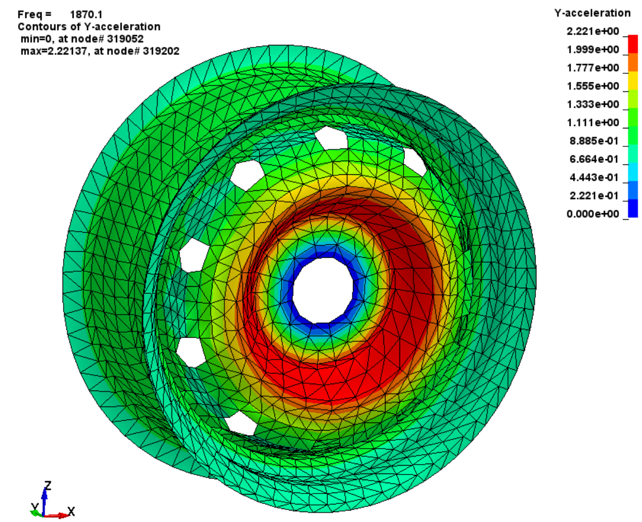
- Acceleration is applied via the edge of the central hole for 1-2000 Hz.
- Total number of nodes: 1589
- Total number of elements: 3051

Y-acceleration by mode-based and direct SSD (1870 hz)

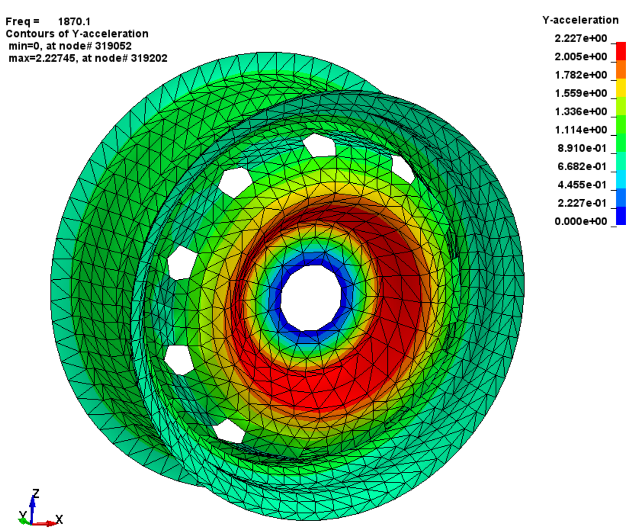
10 modes (fmax = 901 hz)



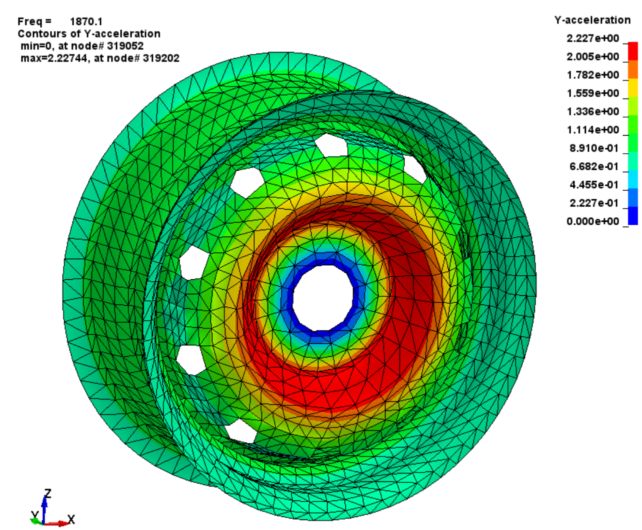
100 modes (fmax = 4690 hz)

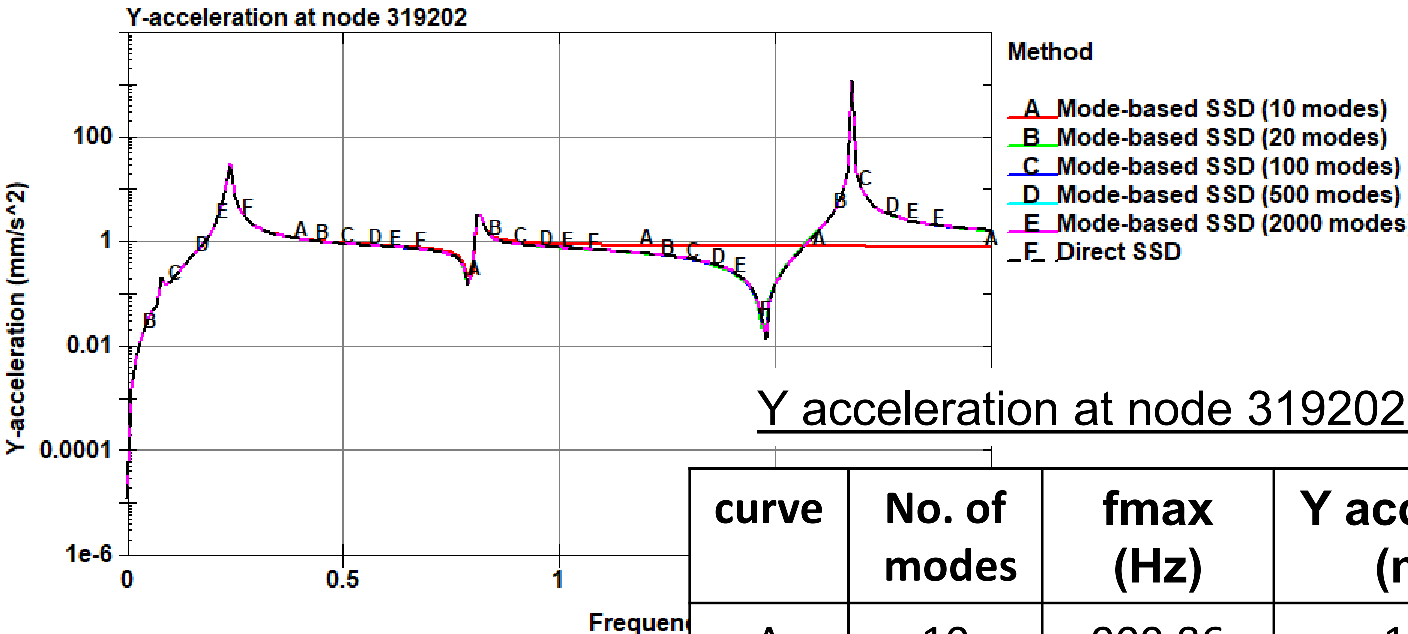


2000 modes (fmax = 55336 hz)



Direct SSD

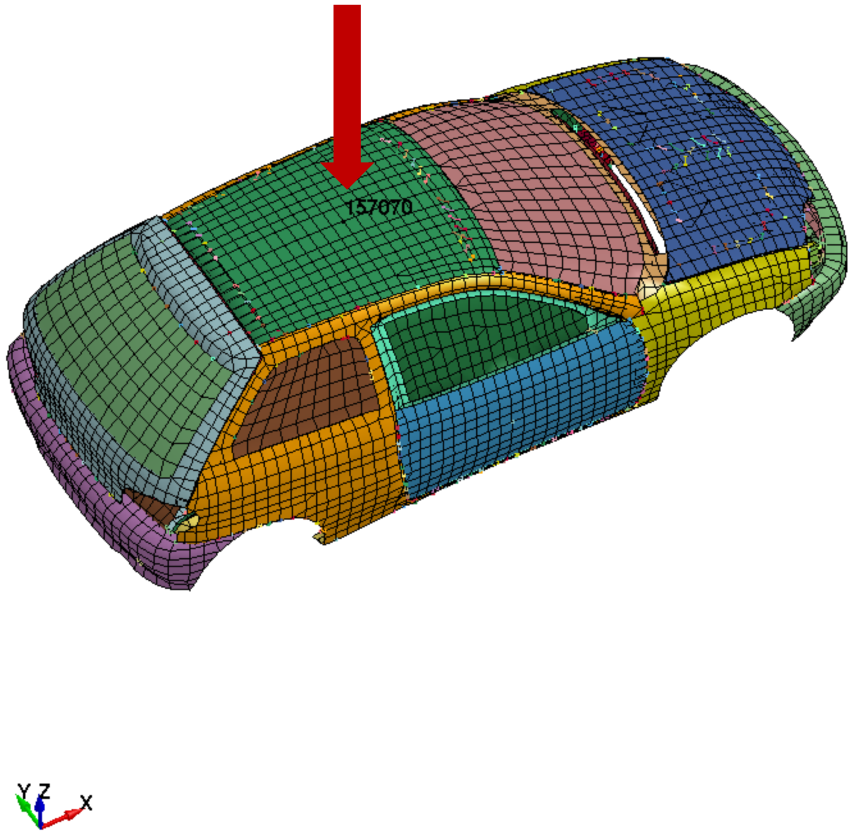




Y acceleration at node 319202 (1870.1 Hz)

curve	No. of modes	fmax (Hz)	Y acceleration (mm/s^2)	CPU (s)
A	10	900.86	1.05581	1.65
B	20	2218.43	2.19535	1.88
C	100	4690.25	2.22137	3.54
D	500	14069.74	2.22743	11.66
E	2000	55335.84	2.22745	39.43
F	Direct		2.22744	22.33

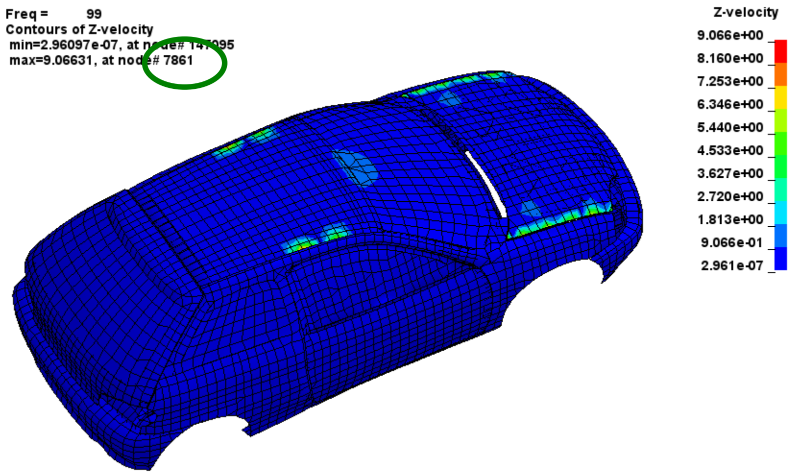
Examples: *3) a simplified car model*



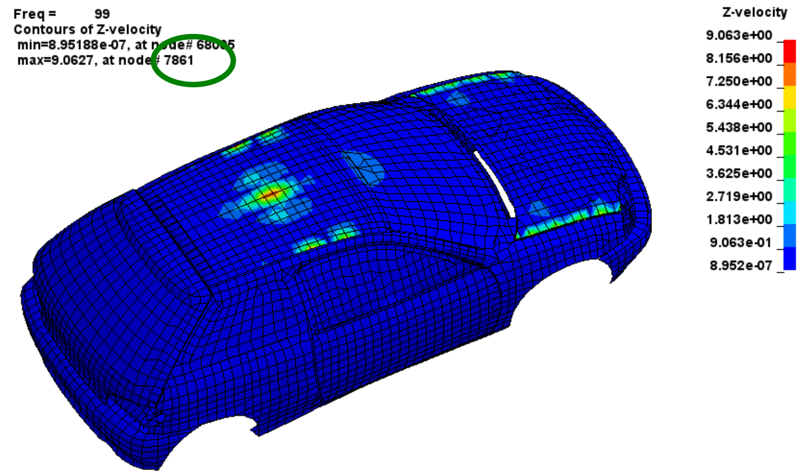
- Harmonic nodal force is applied on the roof (node 157070), for 1-100 Hz.
- Total number of nodes: 15906
- Total number of beams: 10
- Total number of shells: 13206
- Nodal rigid bodies: 1515
- Total number of elements: 13216
- Total number of parts: 96

Z-velocity by mode-based and direct SSD (99 Hz)

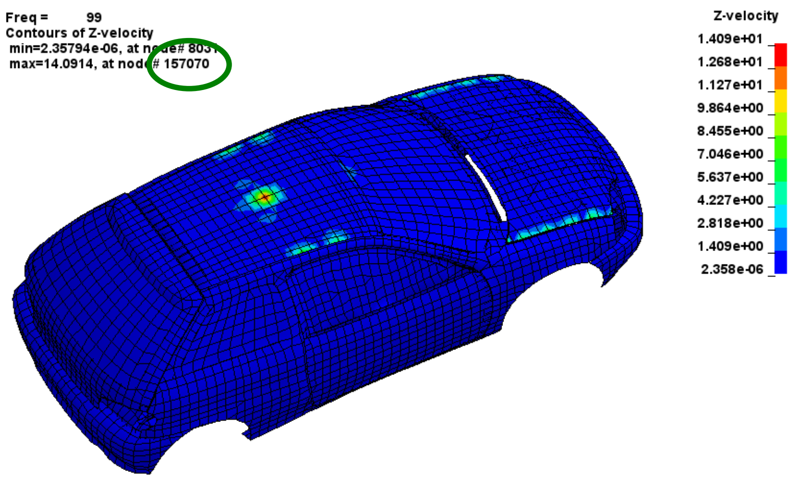
500 modes (fmax = 126 hz)



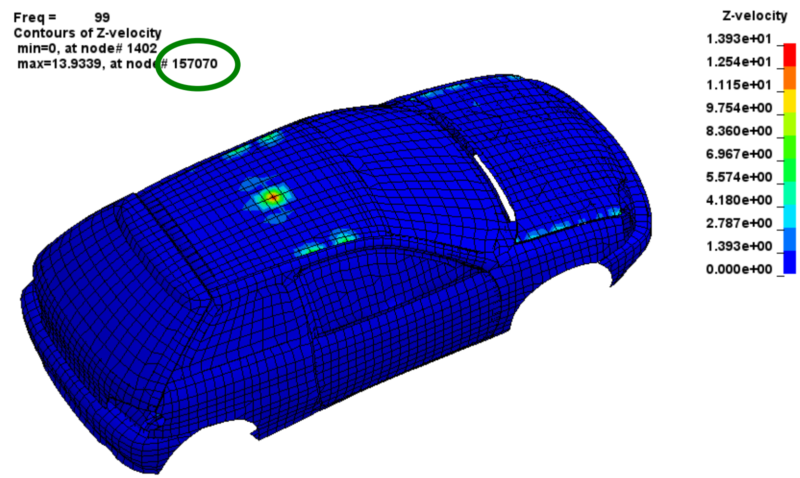
1000 modes (fmax = 195 hz)



5000 modes (fmax = 659 hz)



Direct SSD



Z velocity at loading node 157070 (99 Hz)

No. of modes	fmax (Hz)	Z velocity (mm/s)	CPU (s)
500	125.94	0.123	56.73
1000	194.57	8.533	113.56
2000	298.83	12.233	260.05
5000	658.69	14.091	661.14
Direct		13.934	117.39

Conclusion and future work

- A first version of the direct steady state dynamics solver (SSD) has been implemented to LS-DYNA
- The solution is based on our constrained linear system solver and is very efficient
- Future improvements in plan
  - Incorporation of complex variable frequency dependent properties (e.g. loss and storage moduli of viscoelastic materials)
  - MPP version for large scale problems
  - GMRES and CG solvers, in addition to MF2 solver.
  - More testing and validations

Thank you!