Selective Mass Scaling (SMS)

Theory and Practice

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Content

- Background
  - Is SMS newsworthy?
- Theory and Implementation
  - Difference between CMS and SMS
  - Under the hood
  - When and how to use SMS
- Recent developments
  - Rotational SMS
  - Supported features
- Examples

SMS origins

- Lars Olovsson et.al., *Selective Mass Scaling for Explicit Finite Element Analyses*, Int. J. Num. Methods Eng. (2005)
- Implemented in LS-DYNA for SMP in May 2006
- Supported for MPP in September 2006
- Supported trivial boundary constraints and adaptivity
- Initially intended for metal forming
- Since then things have evolved…

Explicit Finite Elements

- Geometry update

$$\mathbf{a}_n = \mathbf{M}^{-1}(\mathbf{f}_n^e - \mathbf{f}_n^i)$$
$$\mathbf{v}_{n+1/2} = \mathbf{v}_{n-1/2} + \mathbf{a}_n \Delta t$$
$$\mathbf{u}_{n+1} = \mathbf{u}_n + \mathbf{v}_{n+1/2} \Delta t$$

- Mass matrix diagonal

$$\mathbf{M} = \sum_e \mathbf{m}_e \qquad \mathbf{m}_e = \frac{m_e}{n}\mathbf{I}$$

- Stability

$$\Delta t \approx \frac{2}{\omega_{\max}} \approx \sqrt{\frac{\rho}{E}} \min_e l_e = \min_e \sqrt{\frac{m_e}{E l_e}}$$

Conventional Mass Scaling

- Augment mass matrix maintaining diagonal structure

$$\mathbf{M} = \sum_e \left(\mathbf{m}_e + \Delta \mathbf{m}_e \right) \quad \Delta \mathbf{m}_e = \frac{\Delta m_e}{n} \mathbf{I}$$

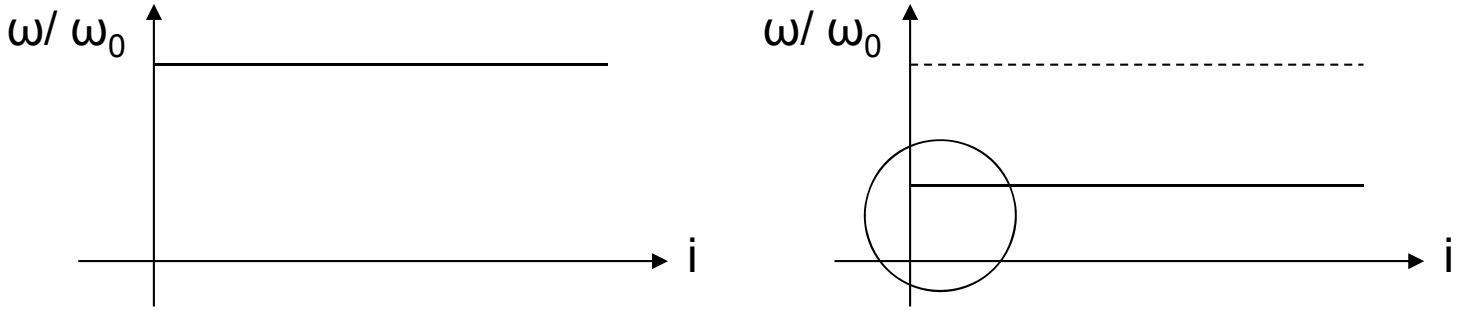
$$\Delta t_{\text{new}} \approx \min_e \sqrt{\frac{m_e + \Delta m_e}{E l_e}} \quad \Rightarrow \quad \frac{\Delta t_{\text{new}}}{\Delta t} = \sqrt{1 + \frac{\Delta m_e}{m_e}}$$

$$t_{CPU} \sim N (t_{CMS} + t_{\text{other}}) \frac{\Delta t}{\Delta t_{\text{new}}}$$

- Shorter simulation times ☺…so far so good…

Problems with CMS

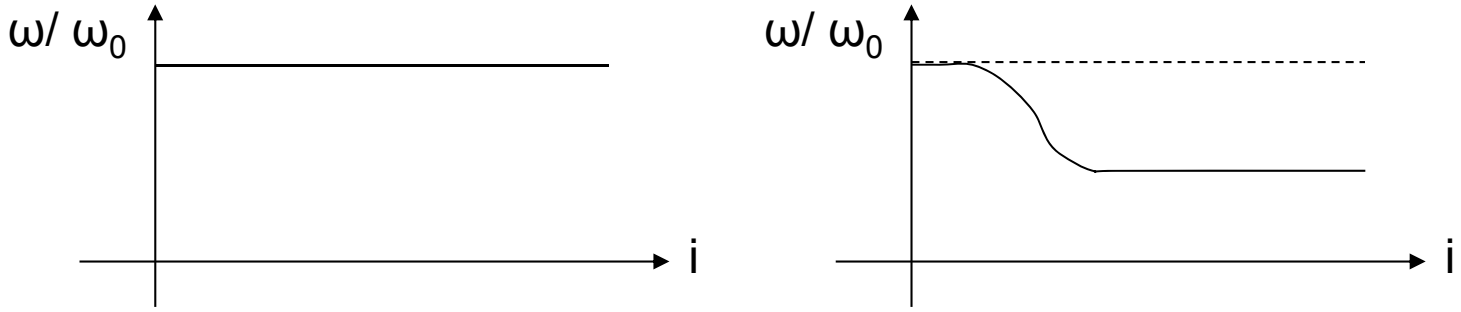
- Adding diagonal mass affects all eigenmodes equally much



- In particular rigid body and low frequency modes are affected
- Structure tends to deform in low frequency modes
- Inertia effects put a practical limit to the time step ☹

SMS idea

- High frequency modes relatively unimportant for structural response, only limits time step
- Suppress high frequency content and leave low freqency modes unaffected



- Modify the structure of the added mass matrix to *select* affected modes

Selective Mass Scaling

- Augment mass matrix projecting out rigid body modes $\mathbf{e}_i$

$$\mathbf{M} = \sum_e \left(\mathbf{m}_e + \Delta \mathbf{m}_e \right) \quad \Delta \mathbf{m}_e = \frac{\Delta m_e}{n} \left(\mathbf{I} - \sum_i \mathbf{e}_i \mathbf{e}_i^T \right)$$

- For rigid body mode, no inertia is added

$$\mathbf{e}_i^T \mathbf{e}_j = \delta_{ij} \quad \Rightarrow \quad \Delta \mathbf{m}_e \mathbf{e}_i = \mathbf{0}$$

- Time step increase the same as with CMS

Example

- 3D membrane
- Projecting out translational rigid body modes only

$$\mathbf{e}_1 = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix}^T \quad \mathbf{e}_2 = \begin{pmatrix} 0 & 1 & 0 \end{pmatrix}^T \quad \mathbf{e}_3 = \begin{pmatrix} 0 & 0 & 1 \end{pmatrix}^T$$

$$\Delta\mathbf{m}_e = \frac{\Delta m_e}{4} \begin{pmatrix} \mathbf{m}_4 & & \\ & \mathbf{m}_4 & \\ & & \mathbf{m}_4 \end{pmatrix} \qquad \mathbf{m}_4 = \frac{1}{4} \begin{pmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{pmatrix}$$

- Generalization to other elements straightforward
- This is the default SMS scheme

Usage

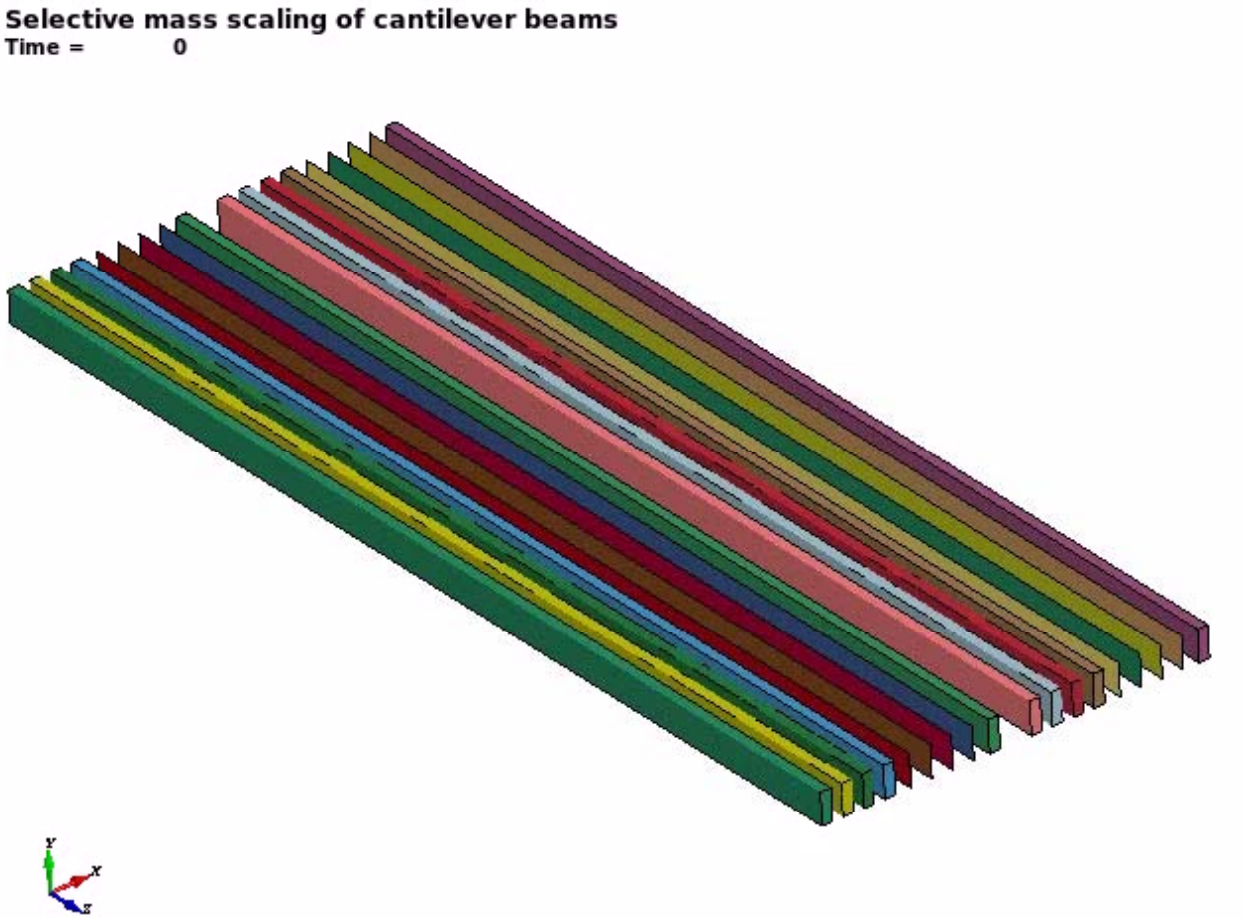
*CONTROL_TIMESTEP

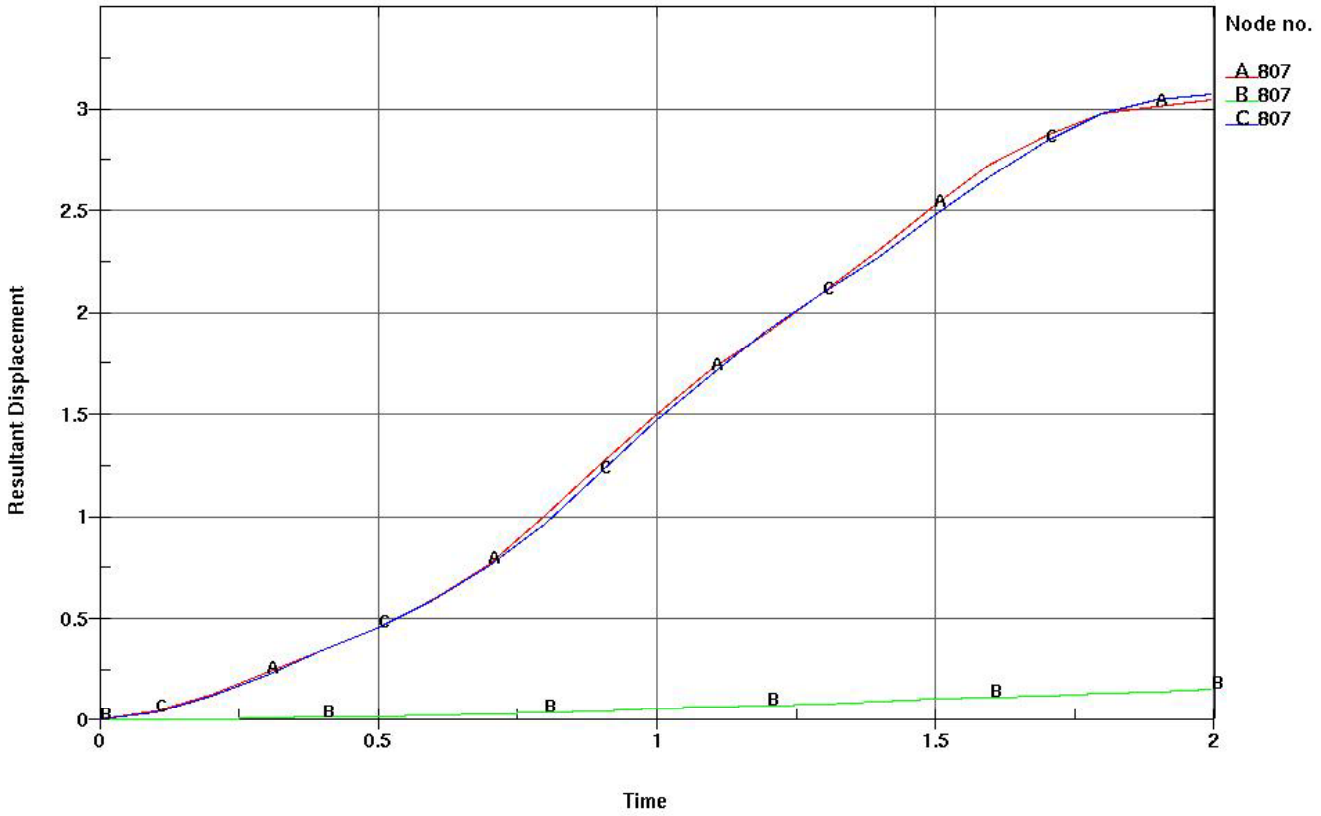
				DT2MS			

		IMSCL			RMSCL		

- SMS can be applied to entire model (IMSCL=1) or a part set (-IMSCL is part set ID)
- Rotational mass scaling activated by RMSCL

Tip-loaded cantilever



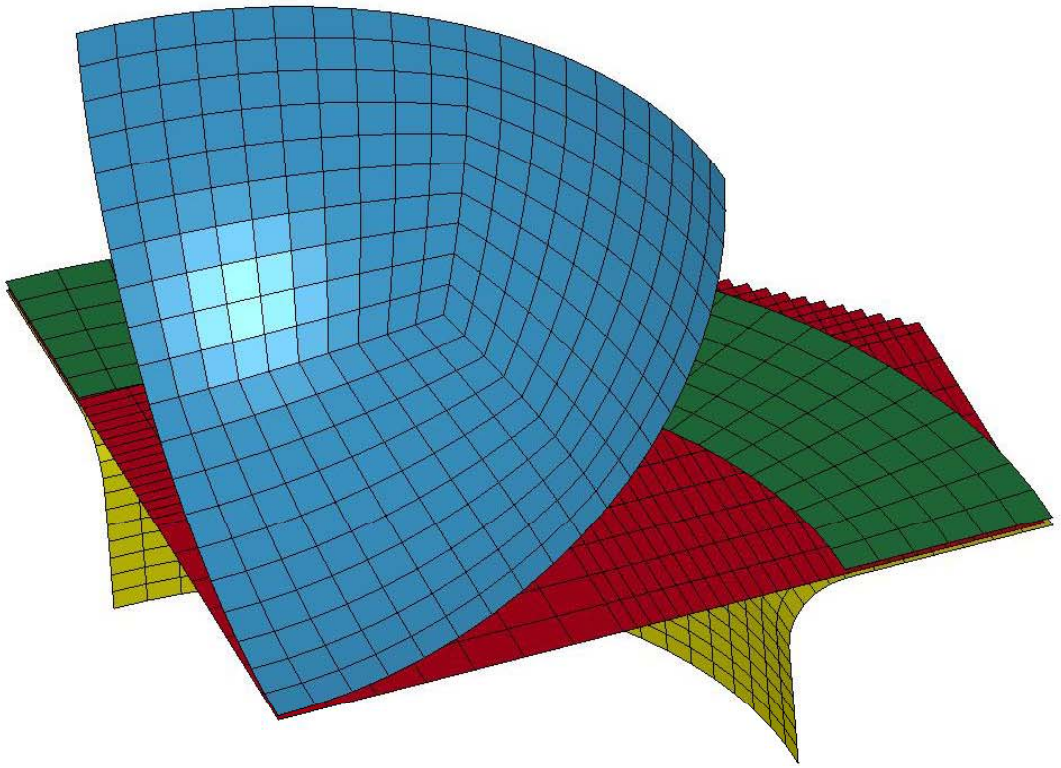


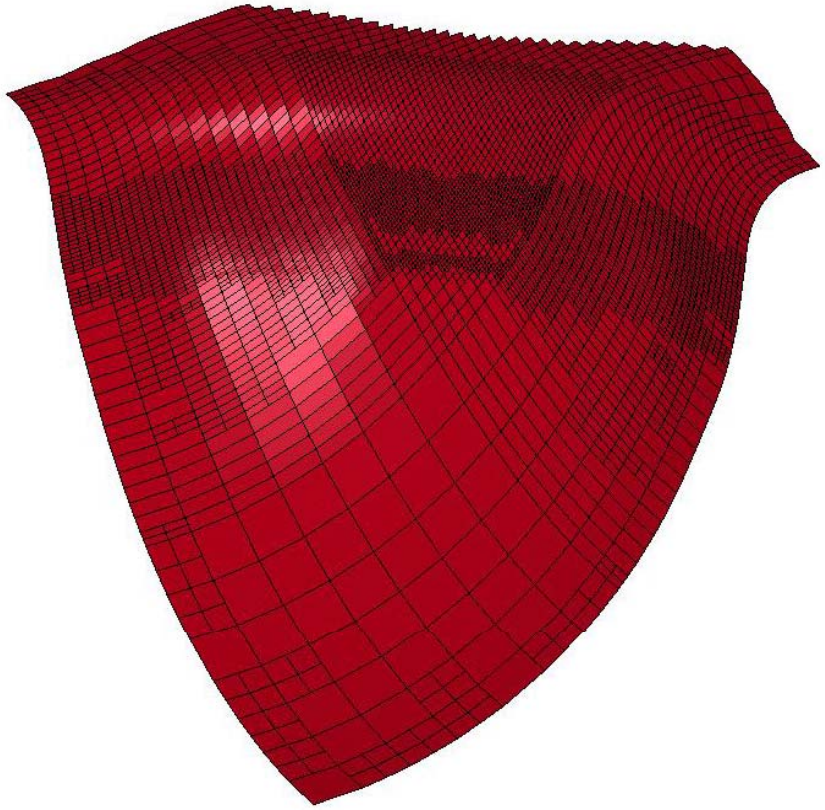
(A) No mass scaling,

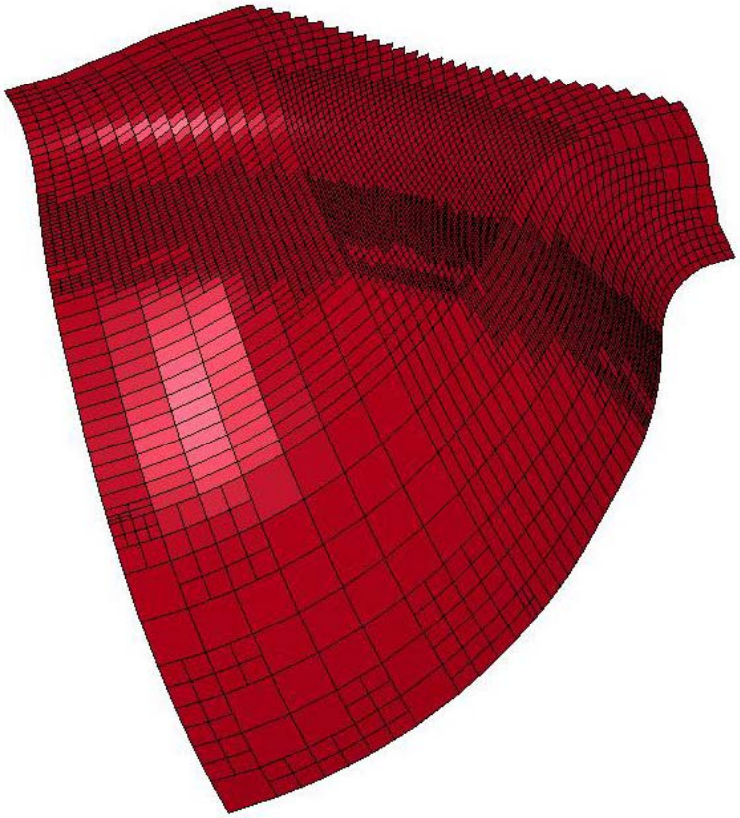
(B) Conventional mass scaling

(C) Selective mass scaling

Deep draw







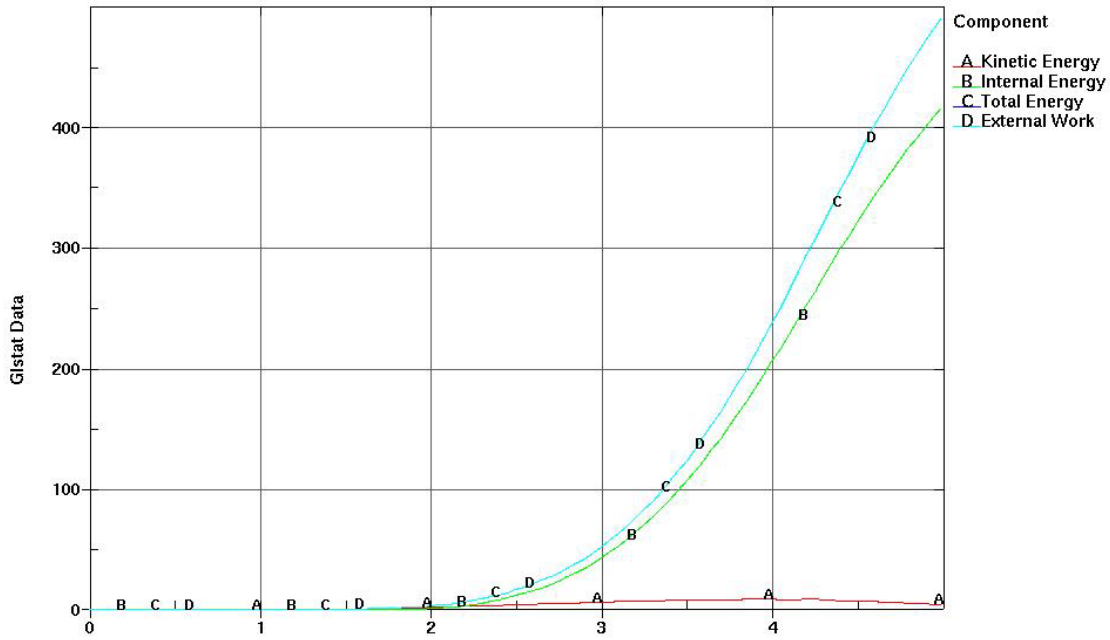
No mass scaling

22 min 6 sec

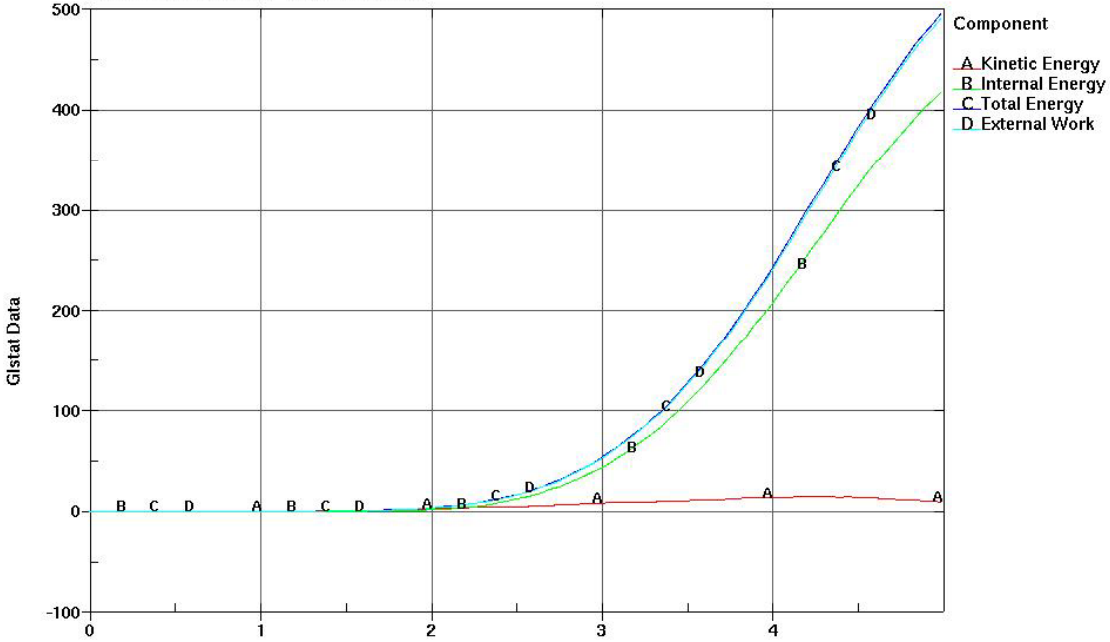
Selective mass scaling

1 min 50 sec

Energy balance –
no mass scaling



Energy balance –
selective mass scaling



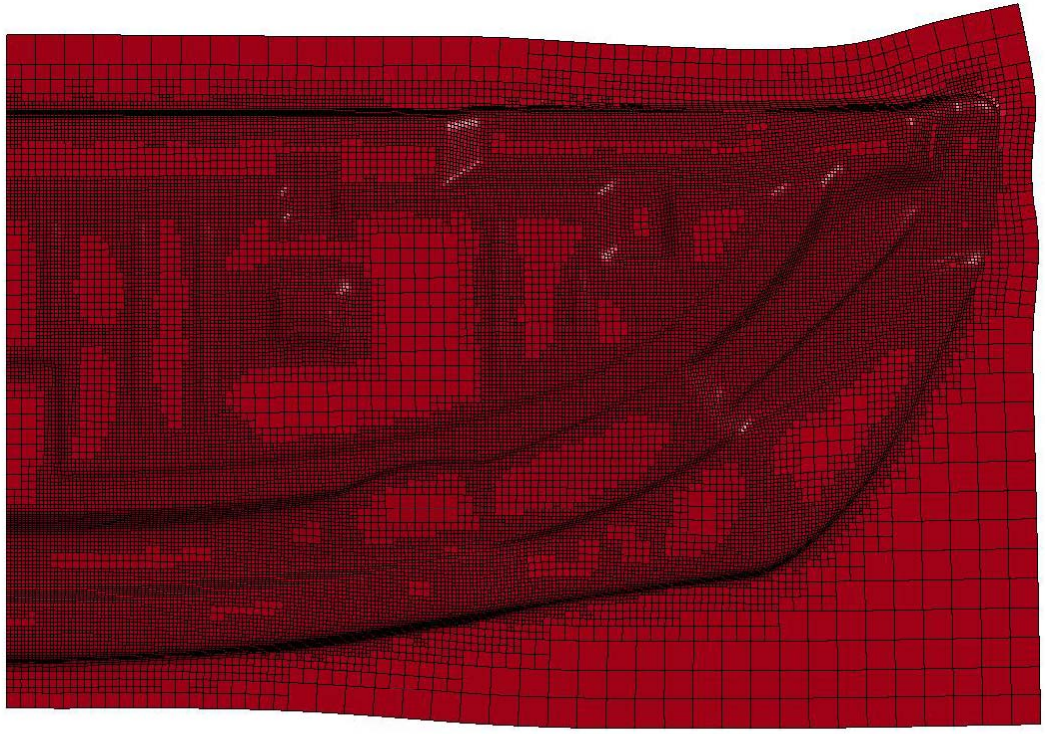
Problem #1 with SMS

- Mass matrix not diagonal, requires solution of linear system of equations $\mathbf{Ma} = \mathbf{f}$
- Solved using a Preconditioned Conjugate Gradient (PCG) with Jacobi preconditioner
- Linear convergence, number of iterations depends on condition number of system matrix $\mathbf{M}$

$$\left.\begin{aligned} n_{\text{iter}} &\sim \sqrt{\kappa(\mathbf{M})} \sim \frac{\Delta t_{\text{new}}}{\Delta t} \\ t_{\text{iter}} &\sim N \end{aligned}\right\} \quad t_{CPU} \sim N\left(t_{SMS} + t_{\text{other}}\frac{\Delta t}{\Delta t_{\text{new}}}\right)$$

- Saturation in CPU time, manifested in large problems

SMS on Adaptive Fender



Time step	1	5	10	15	20
Speedup	1	1.88	2.13	2.06	1.58

Modelling recommendations

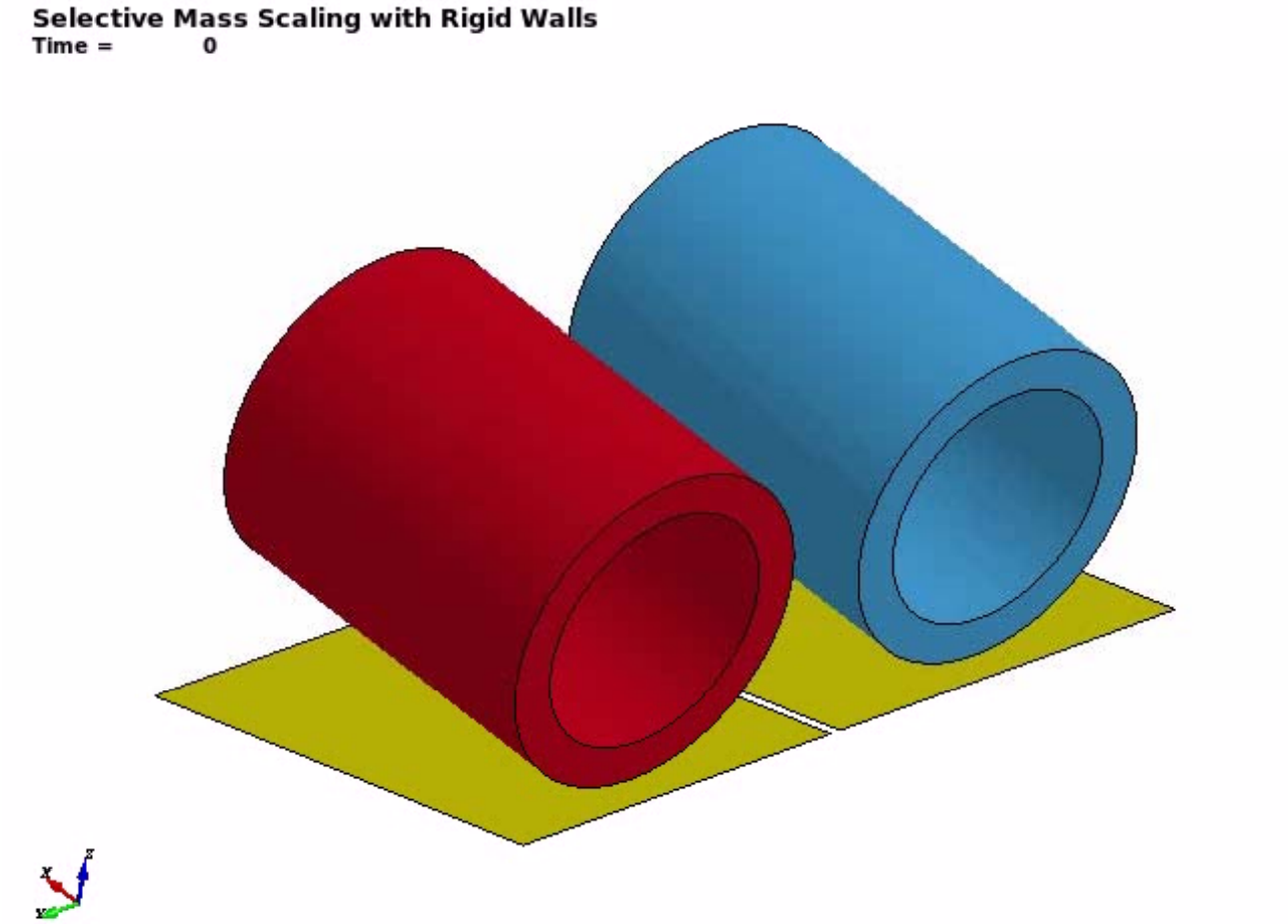
- Apply SMS to critical parts that require fine mesh
  - Spotwelds
  - Bolts
  - Steering wheel
  - Adhesive bondings
- Choose time step with care
  - Beyond some value nothing is gained, only inertia is added
  - Problem dependent, trial and error

Problem #2 with SMS

$$\left.\begin{aligned}\mathbf{a} &= \mathbf{a}_I + \mathbf{a}_D \\ \mathbf{a}_D &= \mathbf{C}\mathbf{a}_I + \mathbf{a}_C\end{aligned}\right\} \quad \underbrace{\tilde{\mathbf{C}}^T\mathbf{M}\tilde{\mathbf{C}}}_{\mathbf{M}_I}\mathbf{a}_I = \underbrace{\tilde{\mathbf{C}}^T\left(\mathbf{f} - \mathbf{M}\mathbf{a}_C\right)}_{\mathbf{f}_I}$$

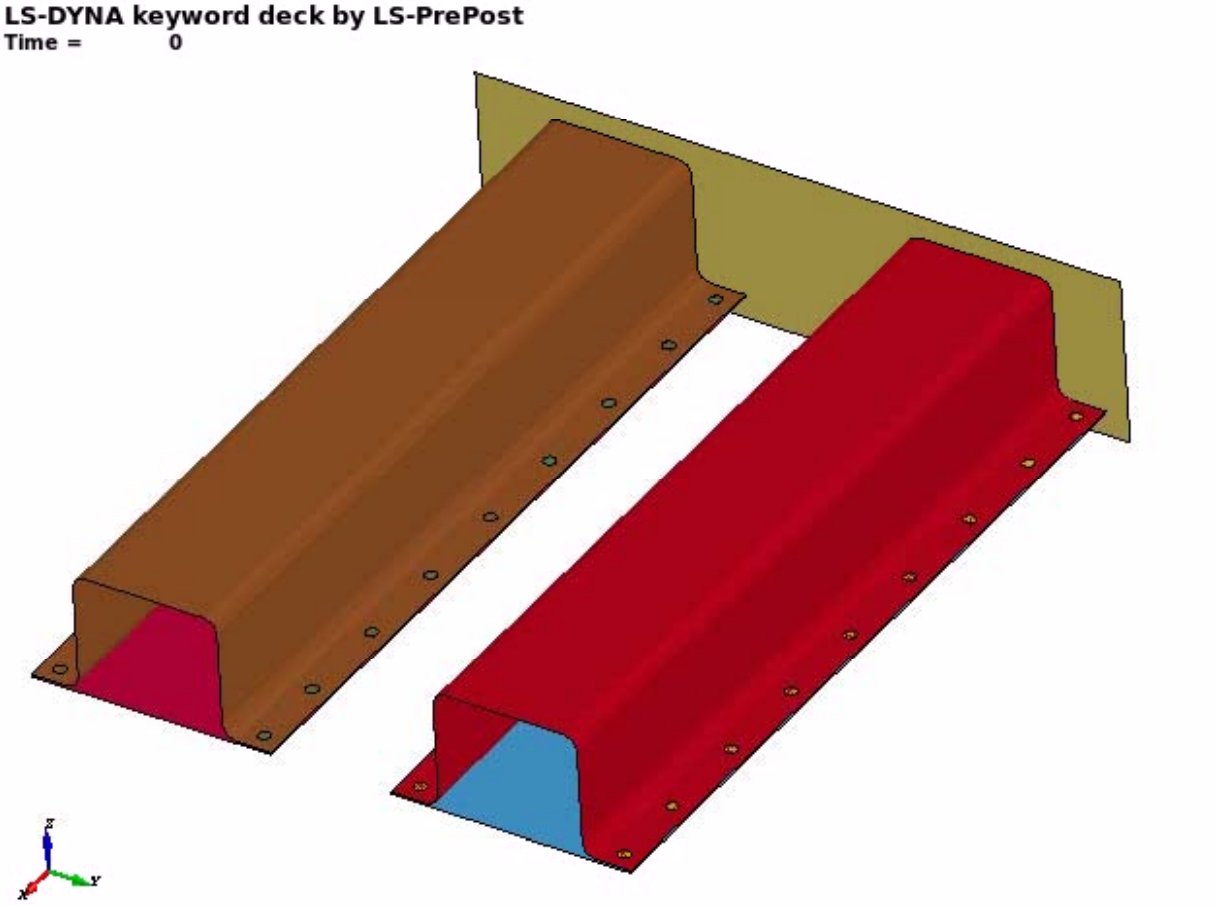
- Each constraint imposed directly on accelerations must be individually treated
  - Boundary prescribed motion
  - Boundary SPC
  - Adaptivity
  - Rigid bodies (including nodal rigid bodies)
  - Rigid walls
  - Tied contact
  - …

Planar rigid walls



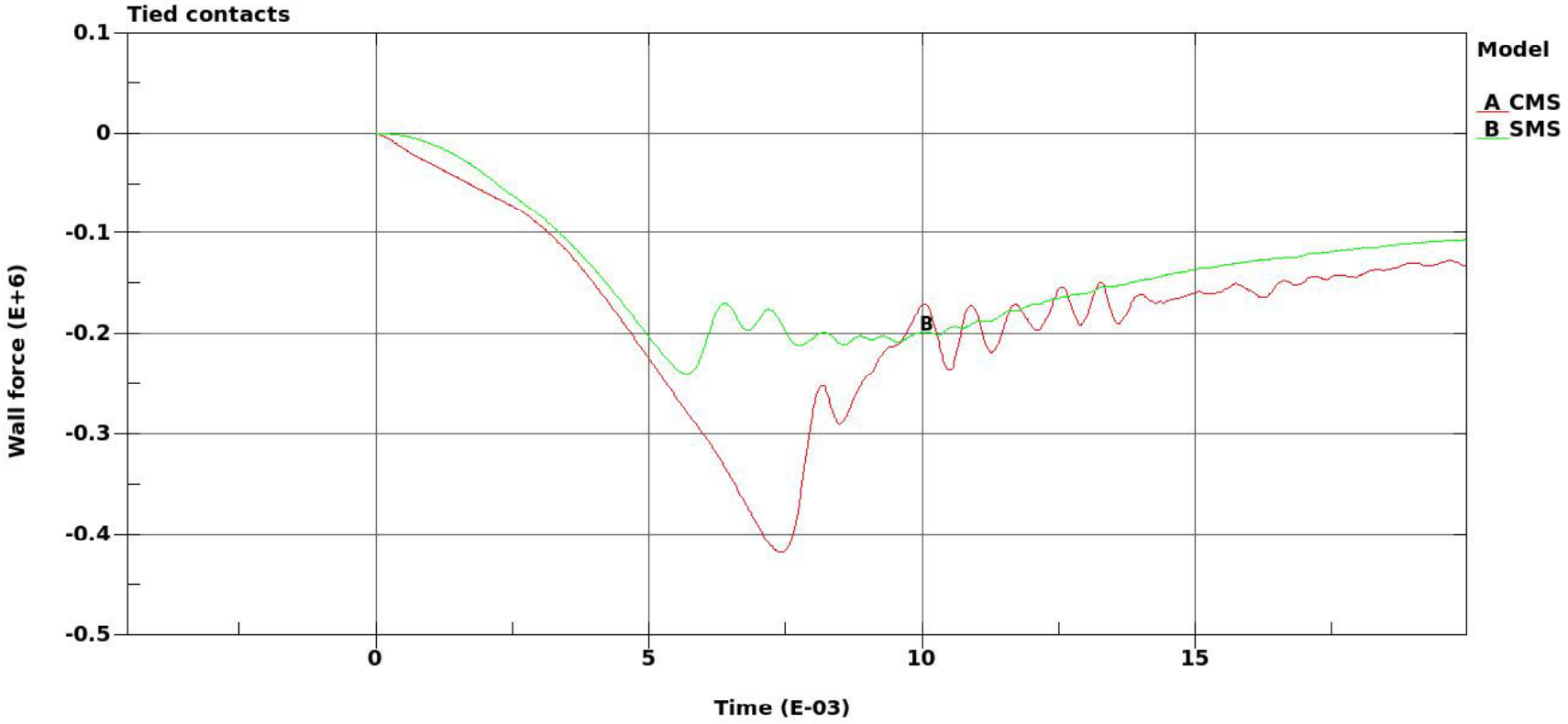
- Implemented March 2009

Tied contacts

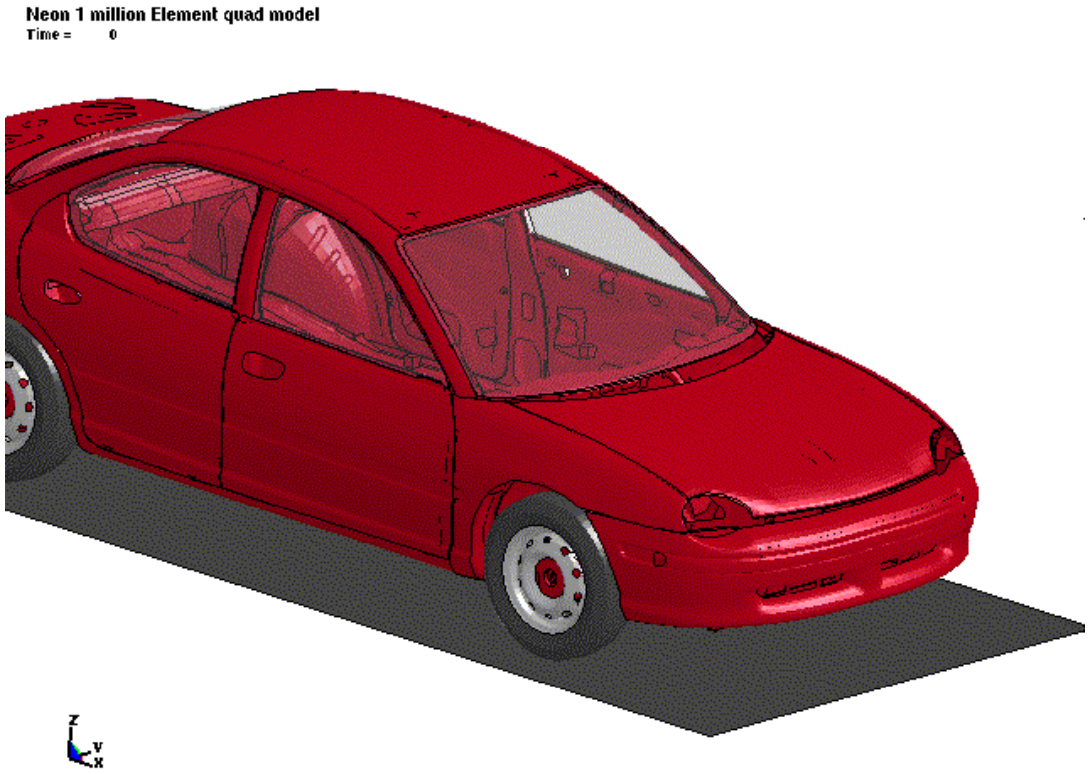


- Implemented October 2010

Peak buckling force

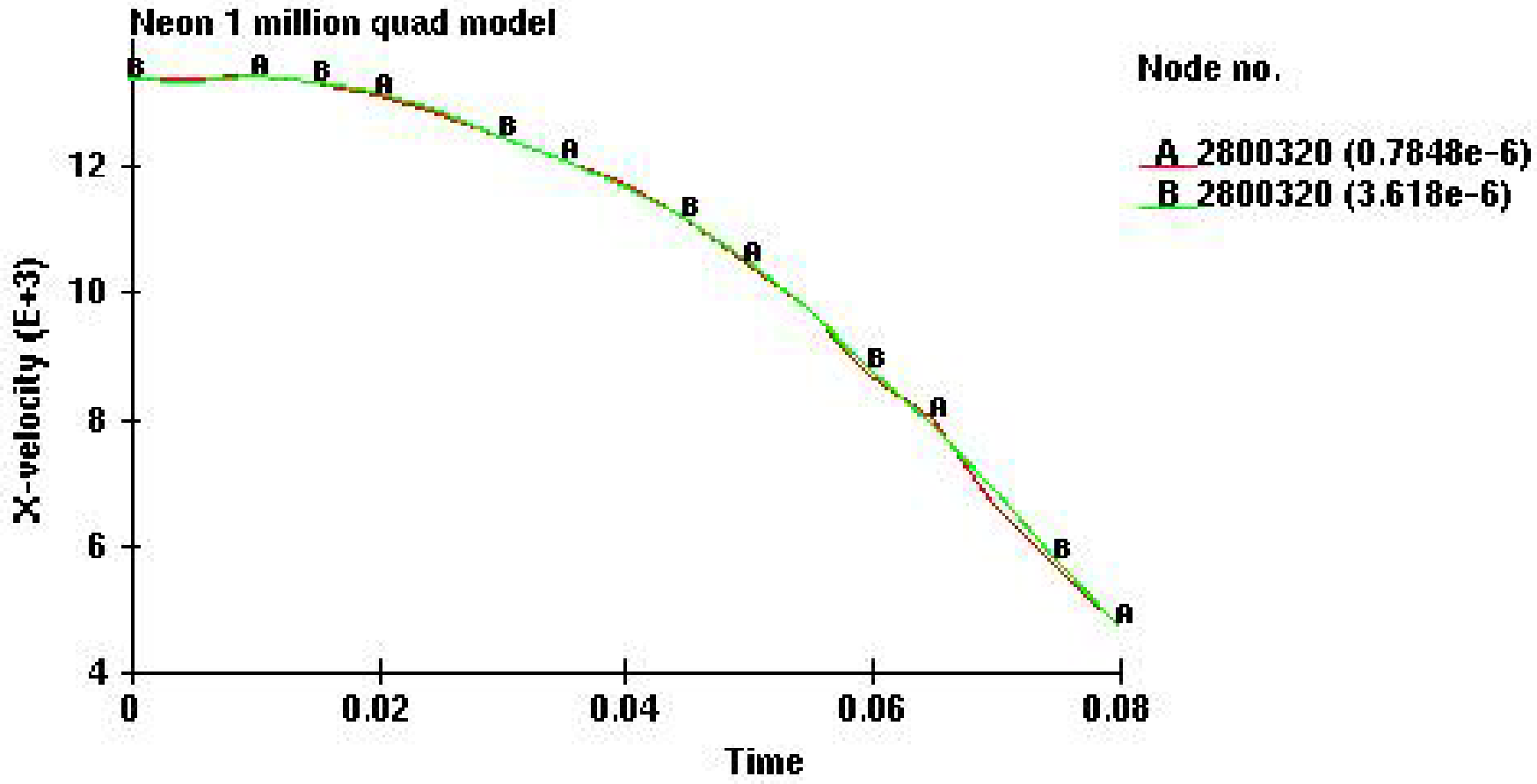


NCAC Neon model



1056383 quad shells
130 beams
2852 solids
1 contact for the entire model
Termination time 0.080 secs
Timestep 3.618e-6 secs
Ascii and binary outputs disabled.
Pre-decomposed with 1cpu

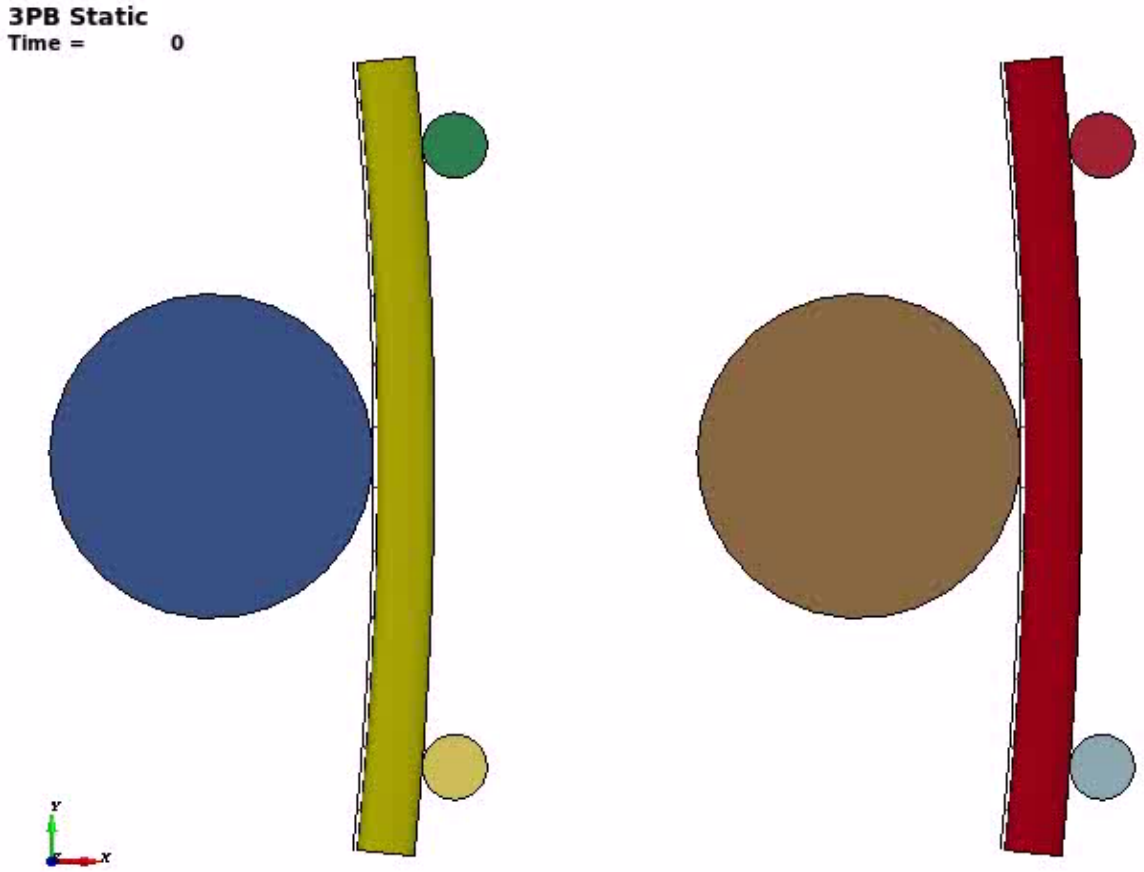
NCAC Neon model



NCAC Neon model

128x2x4 Dt=7.85e-7 8% mass increase Conventional mass scaling	6 minutes 18 secs
128x2x4 Dt=3.618e-6 Selective mass scaling *Ongoing development to support more features for selective mass scaling*	5 minutes

Geometric rigid walls



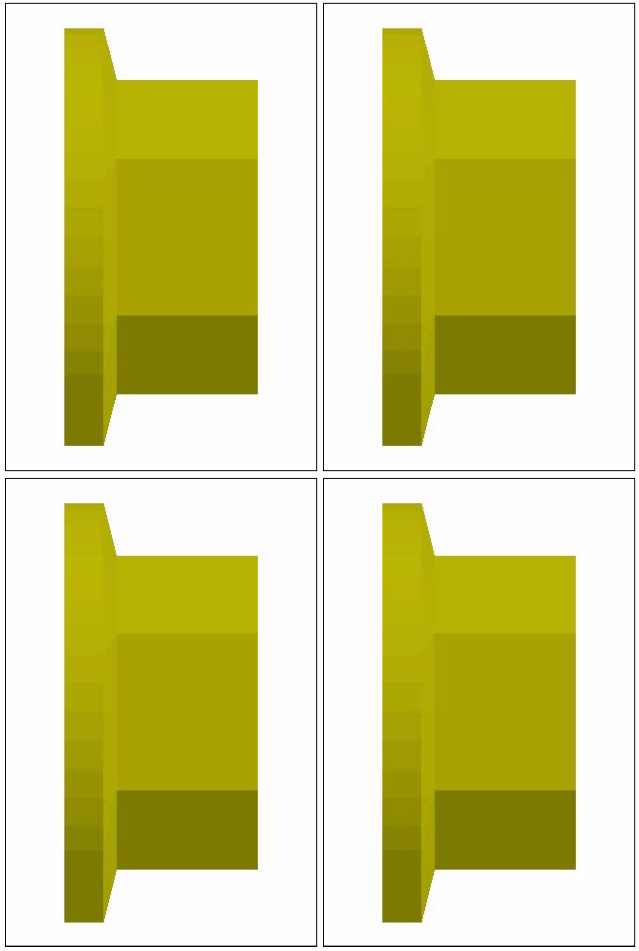
- Implemented June 2011

Rotational SMS

- Include rotational rigid body modes in projection of added mass matrix
- Further reduce inertia for problems involving rotations
- Coupled dimensions makes the scheme CPU intensive
- Practical use remains to be seen

Rotational SMS

No mass scaling



Selective mass scaling

Rotational selective mass scaling

Conventional mass scaling

Summary

- SMS increases the stable time step in explicit simulations without significantly affecting inertial properties
- It has evolved to be an important ingredient in automotive industry
- It requires some experience for maximal efficiency
- It is not a final product but continuously developed to support new features added and/or required in the front end of simulations