LSTC Livermore Software Technology Corp.

LS-DYNA

Acoustics and NVH in LS-DYNA®

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Outline

1. Introduction
2. Transient FEM acoustics
3. Frequency domain BEM Acoustics
4. Frequency domain FEM Acoustics
5. NVH application
6. Future developments

1.

INTRODUCTION

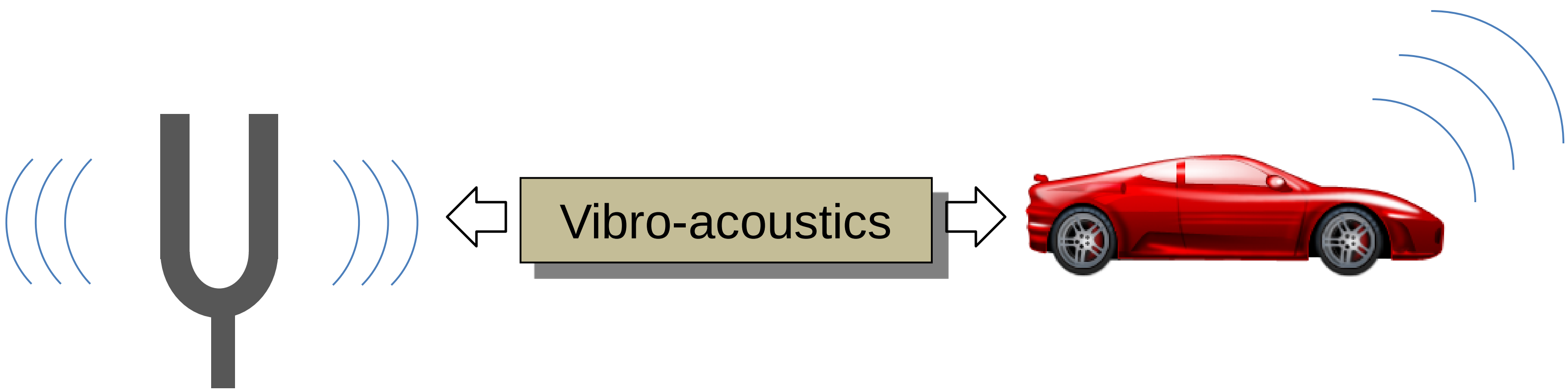
What is acoustics?

*"**Acoustics** is the interdisciplinary science that deals with the study of all mechanical waves in gases, liquids, and solids including vibration, sound, ultrasound and infrasound"*

From **wikipedia**

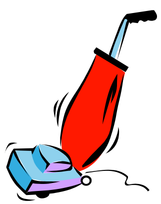
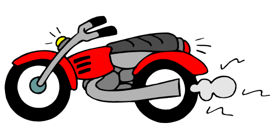
"The scientific study of sound, especially of its generation, transmission, and reception"

From **thefreedictionary**



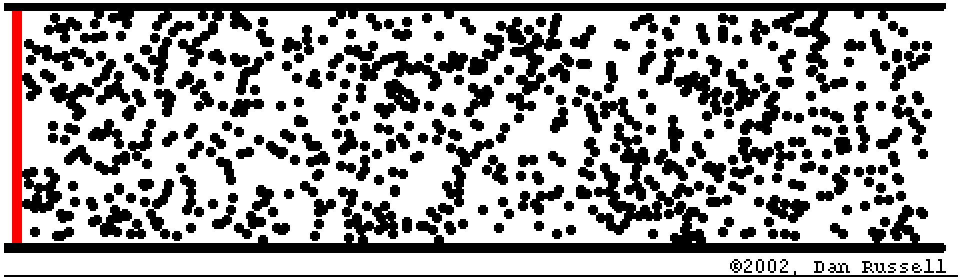
Sound Pressure Level (dB) of typical sounds

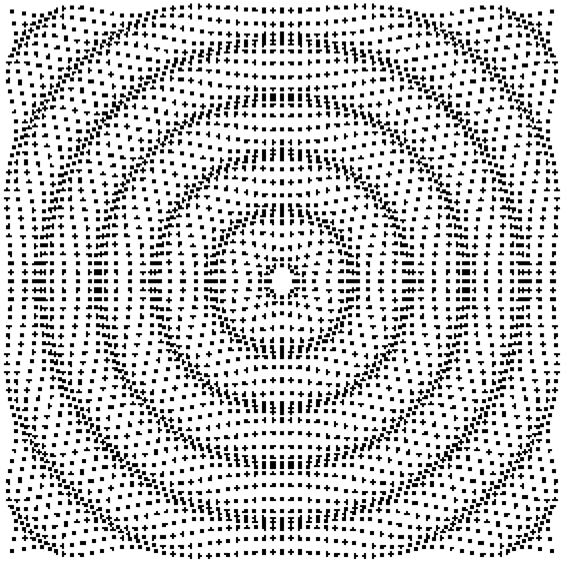



Noise source	dB
Normal breathing	10
Quiet bedroom	20
Quiet conversation	30
Normal conversation	50
Loud television	60
Busy traffic, hair dryer	70
Noisy office, vacuum cleaner	80
Gas Lawn Mower(1m)	90
Pneumatic hammer (2m)	100
Accelerating motorcycle (5m)	110
Jet plane take-off (30m)	120
Threshold of pain	130

Acoustic wave





Animation courtesy of Dr. Dan Russell, Grad. Prog. Acoustics, Penn State

Characteristics of acoustic wave

Frequency $f = 1/T$

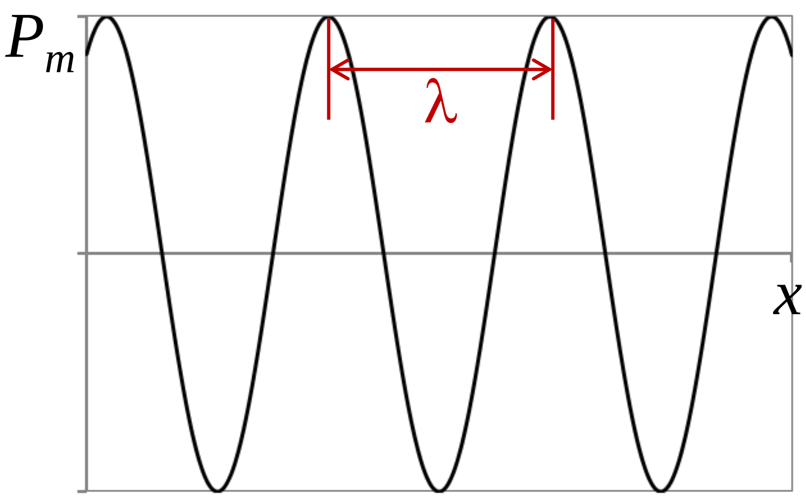
Wave number $k = 2\pi/\lambda = \omega/c$

Wave length $\lambda = c/f = cT$

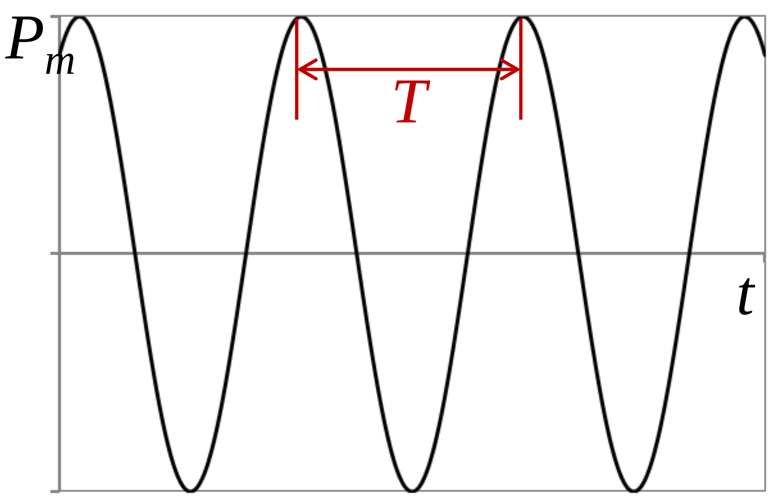
$$P(x,t) = P_m \sin(\omega t - kx)$$
$$= P_m \sin(2\pi f t - kx)$$

$f = 1000\ hz$
- Air: c=340 m/s λ=0.34 m
- Water: c=1500 m/s λ=1.50 m

P(x,t) for t=t_0



P(x,t) for x=x_0



Helmholtz equation

Mass conservation

Linearized momentum equation

Adiabatic process

Homogeneous medium

$$\nabla^2 P - \frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} = 0$$

Time-harmonic waves $P = pe^{i\omega}$

Helmholtz equation

$$\nabla^2 p + k^2 p = 0$$

$$L_P = 10\lg\frac{P^2}{P_0^2}$$

P is the actual pressure

P_0 is the reference pressure (2×10^{-5} Pa for air)

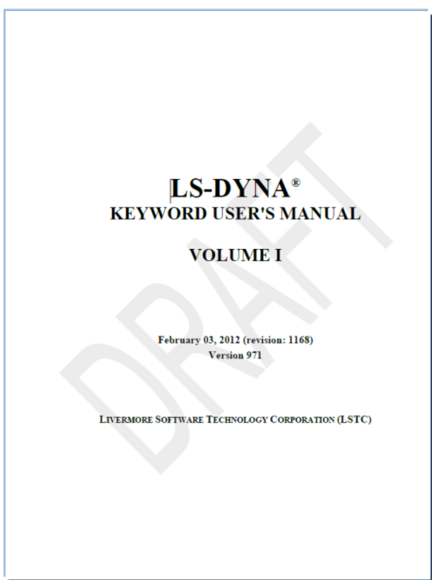
L_P is the sound pressure level (dB).

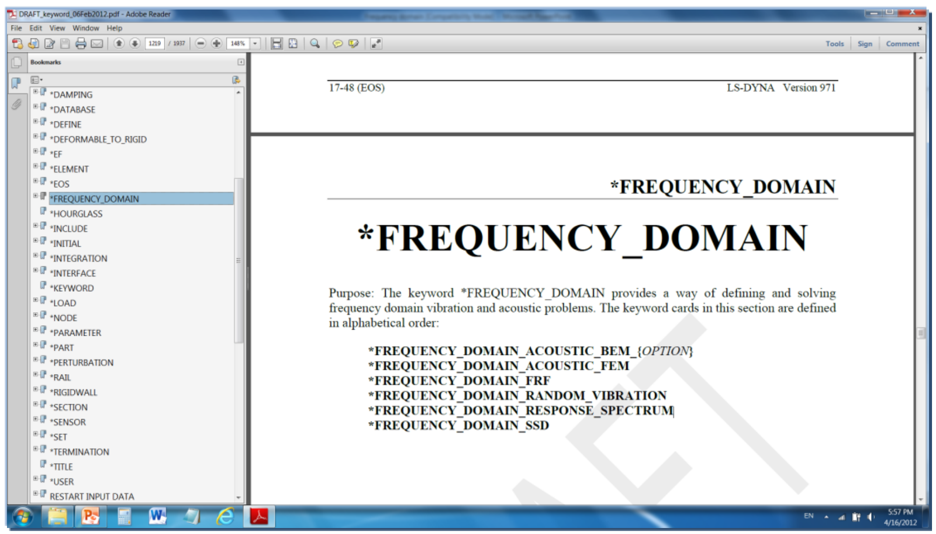
Acoustic solvers in LS-DYNA

***MAT_ACOUSTIC**

FREQUENCY_DOMAIN_ACOUSTIC_BEM_*{OPTION}

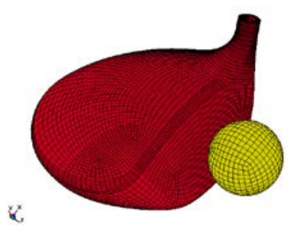
***FREQUENCY_DOMAIN_ACOUSTIC_FEM**





Application of acoustic solvers

- Vehicle NVH
  - *Interior noise*
  - *Exterior radiated noise*
- Acoustic design of sports products
- Transportation acoustics
- Noise control
- Music instruments
- Architectural acoustics (auditorium, conference room)

What is NVH?

NVH stands for **Noise**, **Vibration** and **Harshness**.

Noise:

In common use, the word “Noise” means any unwanted sound. Acoustic noise can be anything from low-level but annoying to loud and harmful. It is also defined as any unpleasant or unexpected sound created by a vibrating object. The human audible sound is in 20-20000 Hz.

Vibration:

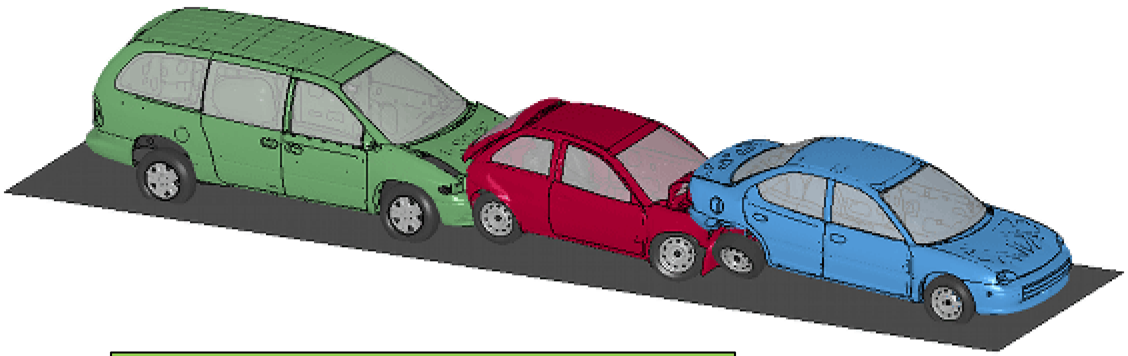
Vibration is defined as any objectionable repetitive motion of the structure, back-and-forth or up-and-down.

Harshness:

Harshness refers to the qualitative assessment of noise and vibration.

The study of sound and vibration are closely related.
Sound, or "pressure waves", are generated by vibrating structures; the pressure waves can also induce the vibration of structures (e.g. ear drum). Thus when trying to reduce noise it is often a problem in trying to reduce vibration.

Application of LS-DYNA in automotive industry



One code strategy

Crashworthiness

Occupant Safety

NVH

Durability

- In automotive, one model for crash, durability, NVH shared and maintained across analysis groups
- Manufacturing simulation results from LS-DYNA used in crash, durability, and NVH modeling.

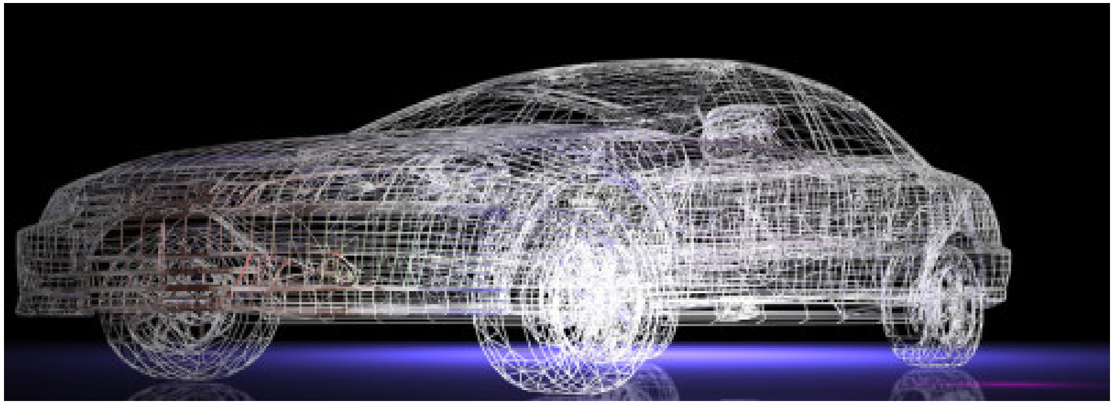
"All-in-one" package

What capabilities are required for LS-DYNA to run NVH simulation?

- Modal analysis
- Frequency response functions
- Vibration solver
- Acoustic solver
- Pre and post processing tools
- Optimization tools

Target

Optimize NVH performance & keep NVH response within design limits



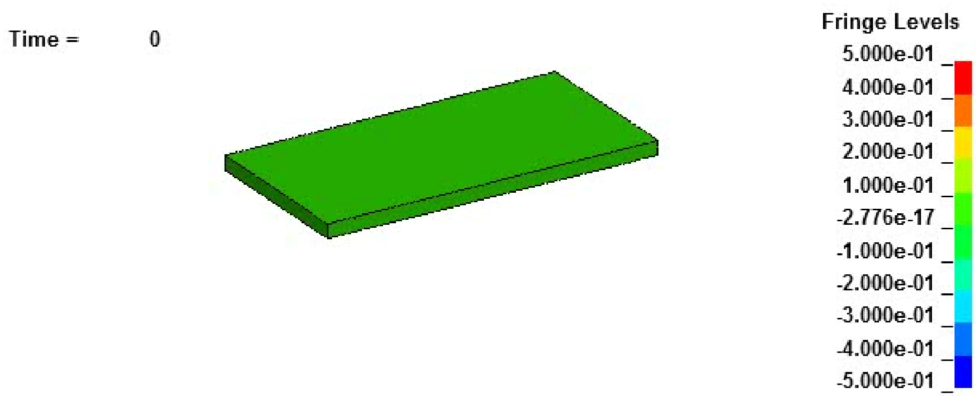
2.

TRANSIENT FEM ACOUSTICS

Transient Acoustic Material Model

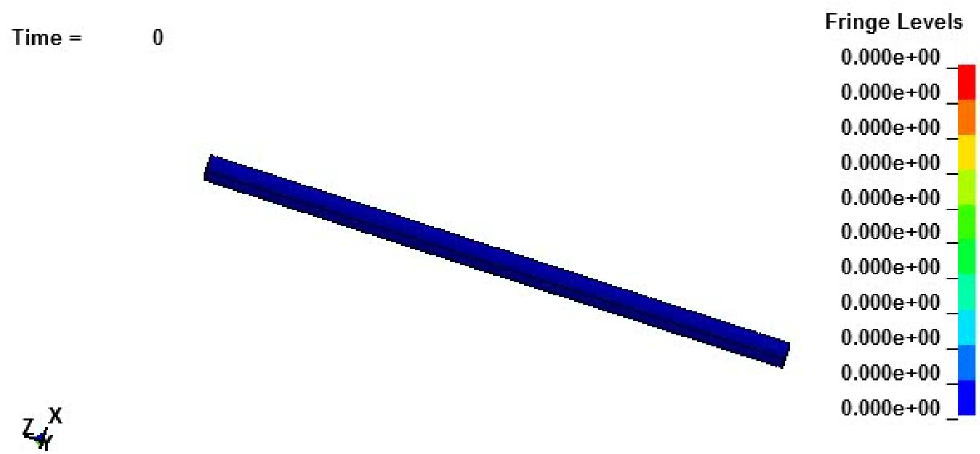
- Acoustic domains are identified in LS-DYNA with
  - Element formulations ELFORM=8 and ELFORM=14
    - ELFORM=8 is 1-pt integrated volume element supporting hexahedral, pentahedral and tetrahedral configurations. Automatically branches to appropriate element shape functions
    - ELFORM=14 is 8-pt integrated volume element mainly intended for hexahedral configurations. More accurate than 1-pt hex in distorted forms. Does not automatically branch for pents and tets
  - Material model ***MAT_ACOUSTIC**
    - Requires mass density and fluid sound speed
    - Optionally, a cavitation flag to invoke bilinear fluid cavitation model
    - Optionally, a non-dimensional damping parameter to suppress cavitation frothing and enhance stability

  - Optionally, flat free surface geometry, atmospheric pressure and gravity
- Transient acoustic elements possess one degree of freedom at each node
  - Calculations per time step are almost trivial
  - Elements are very fast



Assumptions and Limitations

- ***MAT_ACOUSTIC**
  - linear compressible and inviscid fluid
  - undergoing small displacements and irrotational flow
  - a total (incident + scattered) pressure formulation
- Solutions are explicit, in lock step with the structure
  - time stepping at either the Courant step of the smallest acoustic element or a smaller structural element step



Boundary Conditions

- Boundaries merged with structure or identified with ***BOUNDARY_ACOUSTIC_COUPLING** respond to structural motions
- Boundaries identified with kinematic constraints like ***BOUNDARY_SPC_NODE** are rigid, reflecting boundaries
- Boundaries identified with ***LOAD_SEGMENT_SET** have entrant, distributed pressure
- Boundaries identified with ***BOUNDARY_NONREFLECTING** and ***BOUNDARY_USA_SURFACE** are nonreflecting
- Boundaries left free generate rarefaction waves

Non-Reflecting Boundaries

- ***BOUNDARY_NONREFLECTING** invokes the plane wave approximation
  - effectively rho-cee dashpots
  - works best if arranged for normal incidence
- ***BOUNDARY_USA_SURFACE** invokes the doubly asymptotic approximations of the USA code
  - optional module to LS-DYNA
  - subject to export controls
- ***MAT_ACOUSTIC_PML** is a material model for perfectly matched layer specialized to acoustic formulation
  - employ it at outer boundary with acoustic hex elements

Coupling with Structure

- There are three ways to couple acoustic volume elements with structural elements
  - automatic coupling
  - ***BOUNDARY_ACOUSTIC_COUPLING**
  - ***BOUNDARY_ACOUSTIC_COUPLING_MISMATCH**
- Automatic coupling
  - If the acoustic volume nodes are merged with the structural nodes, and if the faces of the elements are compatible (tria on tria, quad on quad)
  - then the coupling will be automatic
  - limited to one-sided coupling

Quarter model of submerged, fluid filled sphere subject to acoustic step wave

The geometry and properties of the sphere are:

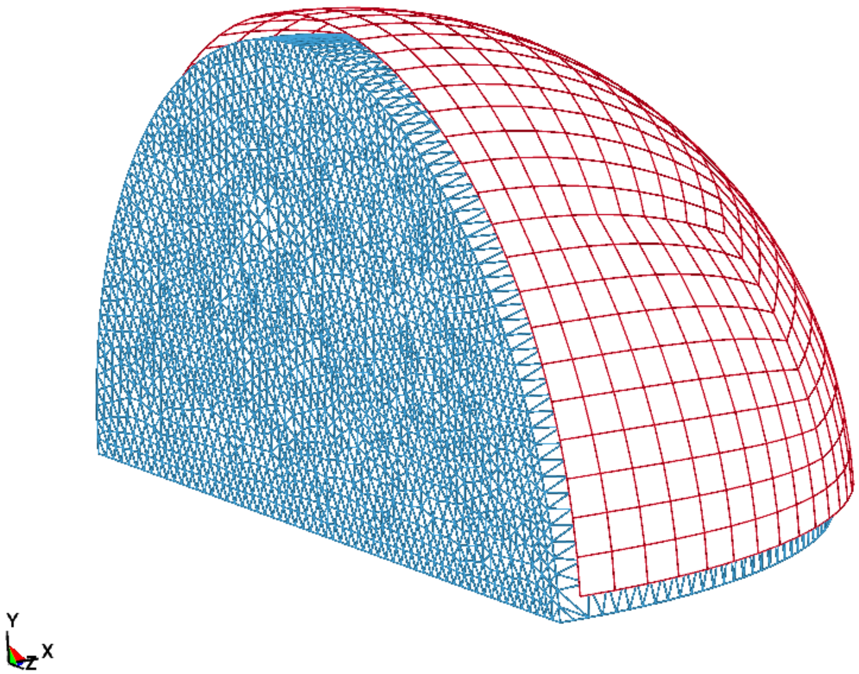
- R = 10.0 in
- t = 0.10 in
- ρ_s = 0.732e-03 lb-sec^2/in^4
- E = 0.29e+08 lb/in^2
- ρ_f = 0.96e-04 lb-sec^2/in^4
- c_f = 60,000 in/sec

The shock loading for a planar step wave:

- P_o = 1 lb/in^2
- z_s = -10.0 in (hit pt)
- z_c = -10000.0 in (source pt)

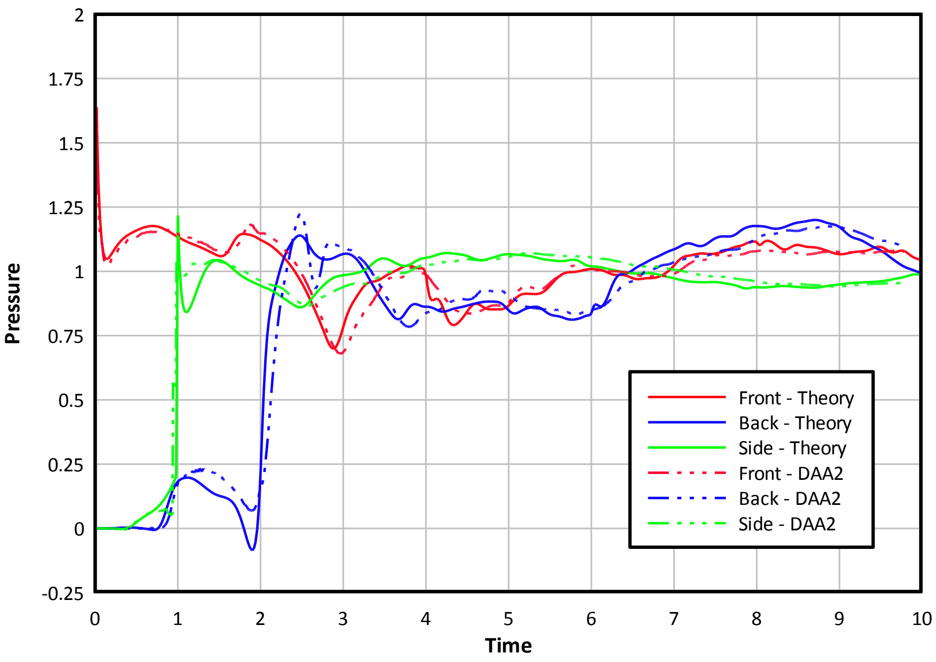
The shock loading for an exponential wave:

- P_o = 1 lb/in^2
- θ = 0.833e-04 sec
- z_s = -10.0 in (hit pt)
- z_c = -30.0 in (source pt)



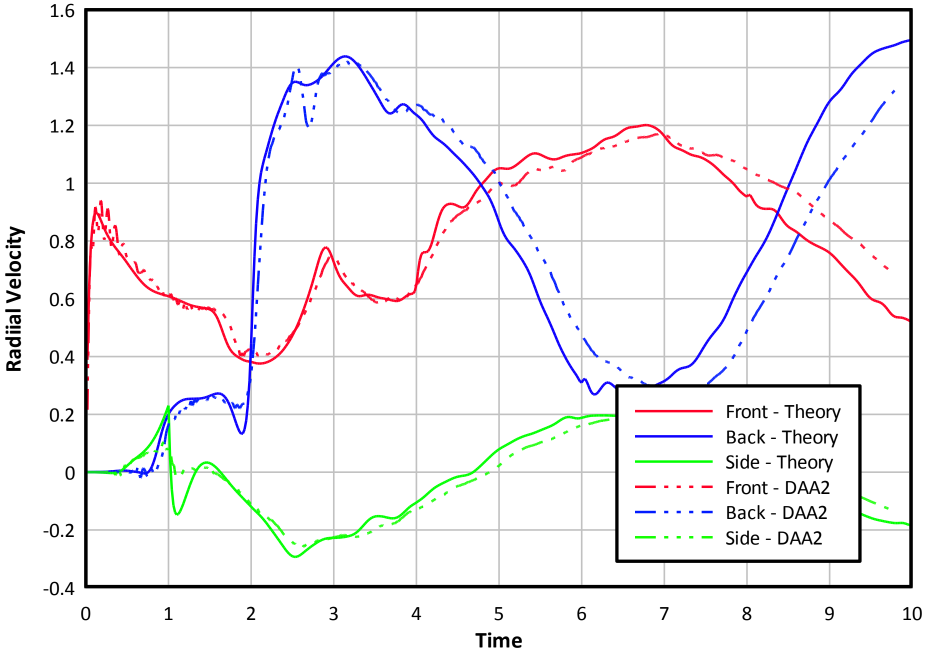
Case 1: Planar Step Wave, Pressure on Sphere

LS-DYNA



Pressure at front, back and crown compared to theoretical solution

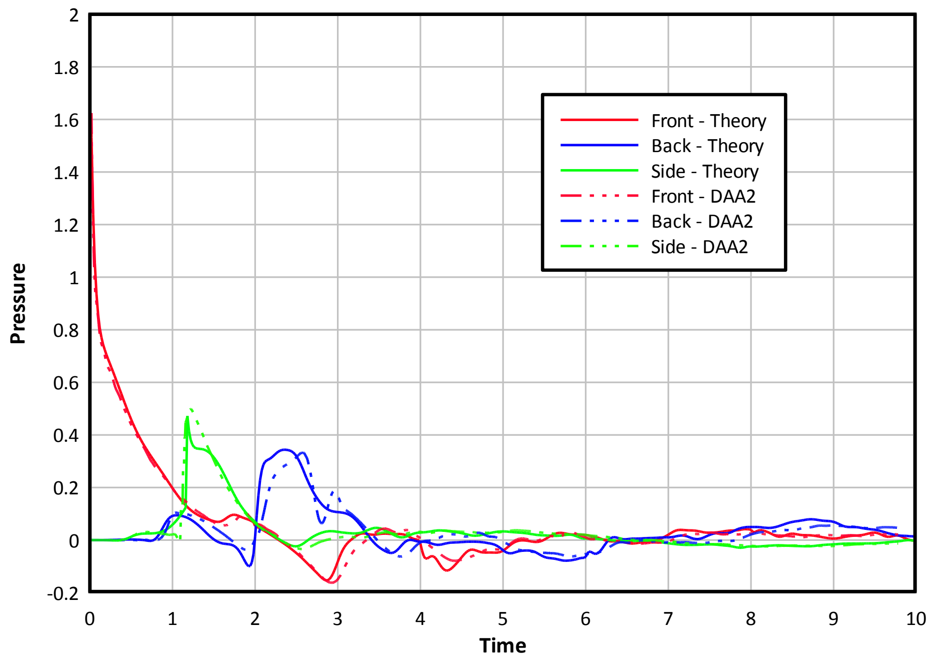
Case 2: Planar Step Wave, Radial Velocity of Sphere



Velocities at front, back and crown compared to theoretical solution

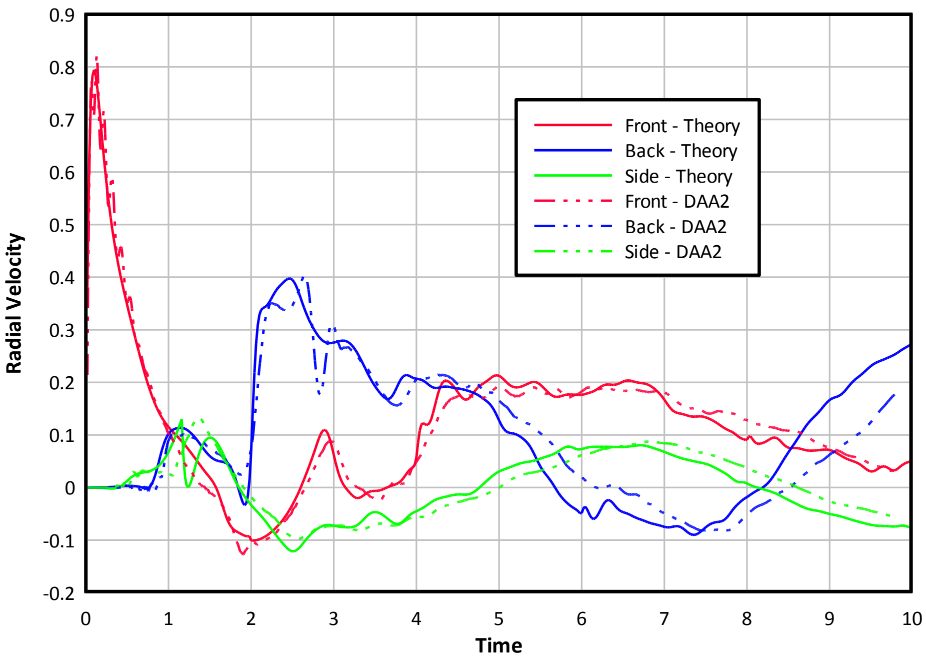
Case 3: Exponential Wave, Pressure on Sphere

LS-DYNA



Pressure at front, back and crown compared to theoretical solution

Case 4: Exponential Wave, Radial Velocity of Sphere

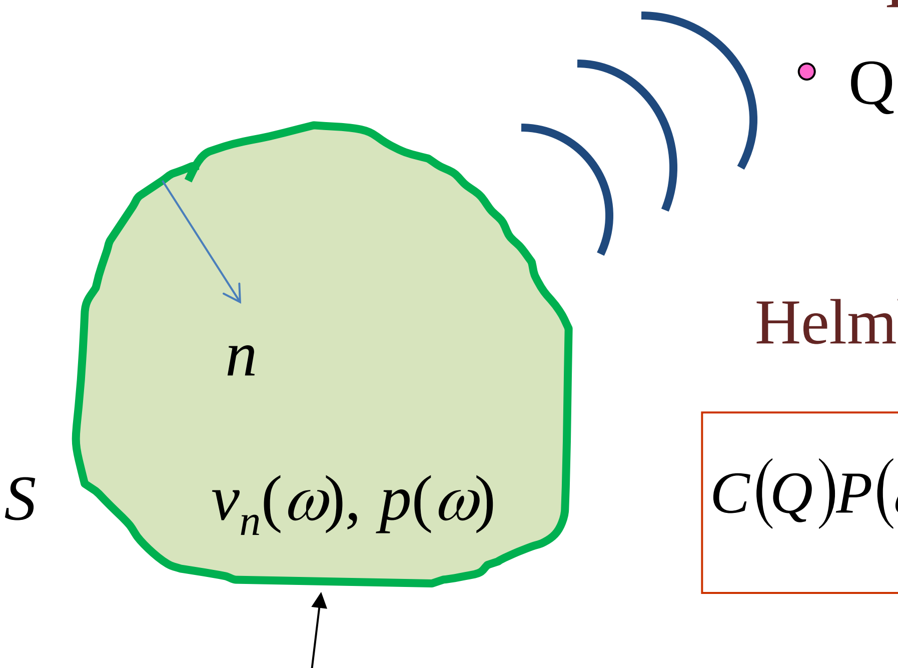


Velocities at front, back and crown compared to theoretical solution

3.

FREQUENCY DOMAIN BEM ACOUSTICS

Helmholtz Integral Equation



Vibrating structure

Fundamental solution

$$G(\omega) = \frac{e^{-ikr}}{4\pi r}$$

Helmholtz integral equation

$$C(Q)P(\omega) = -\int_S \left(i\rho\,\omega v_n(\omega) G + p(\omega)\frac{\partial G}{\partial n} \right) ds$$

$$C(Q) = \begin{cases} 1 & Q \text{ is in the acoustic domain} \\ 1/2 & Q \text{ is on the smooth boundary} \end{cases}$$

$p(\omega)$: pressure at observation point Q
P : pressure on S in frequency domain
v_n: normal velocity on S in frequency domain

BEM (accurate)

- Indirect variational boundary element method
- Collocation boundary element method

They used to be time consuming

A fast solver based on domain decomposition

MPP version

Approximate (simplified) methods

- Rayleigh method
- Kirchhoff method

Assumptions and simplification in formulation

Very fast since no equation system to solve

➢ Collocation boundary element method

✓ Variables: p, v_n

✓ System of equations: nonsymmetrical, complex, fully populated

✓ A dual collocation BEM based on Burton-Miller formulation to solve irregular frequency problem.

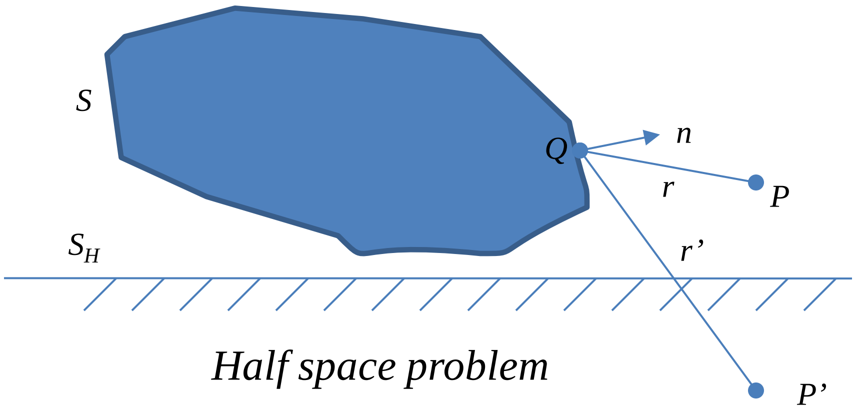
➢ Indirect variational boundary element method

✓ Variables: jump of p, or ∂p/ ∂n, (potential functions)

✓ System of equations: symmetrical, complex, fully populated

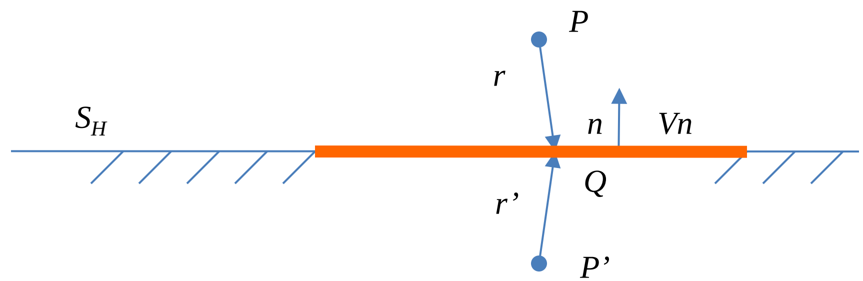
$$A(\omega)x(\omega) = p(\omega)$$

Theory basis for Rayleigh method



Half space problem

Special case when the vibrating surface lies on the reflecting plane



$$G = \frac{e^{-ikr}}{4\pi r}$$

$$P(\omega) = -\int_S \left(i\rho\omega v_n(\omega) G_H + p(\omega)\frac{\partial G_H}{\partial n} \right) ds$$

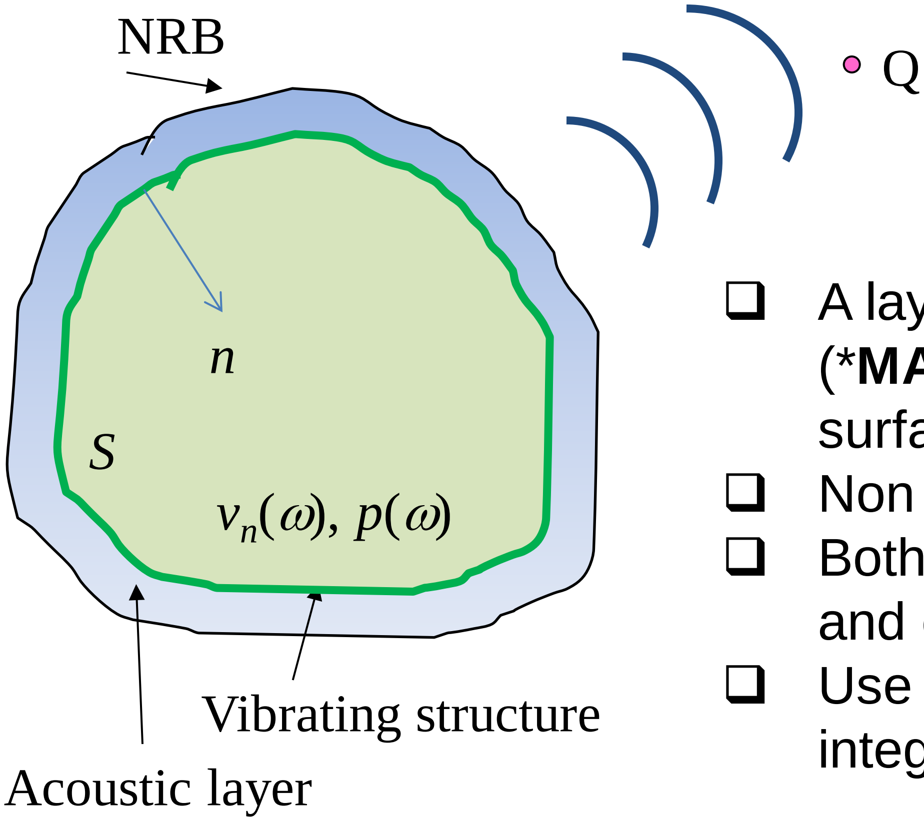
$$G_H = \frac{e^{-ikr}}{4\pi r} + \frac{e^{-ikr'}}{4\pi r'}$$

$$G_H = 2G \qquad \partial G_H / \partial n = 0$$

$$P(\omega) = -\int_S 2 i\rho\omega v_n(\omega) G ds$$

- ❑ Knowing the velocity of structure allows to compute pressure at any location by a simple integral
- ❑ No linear system to be solved
- ❑ Used ONLY for external problems

Theory basis for Kirchhoff method



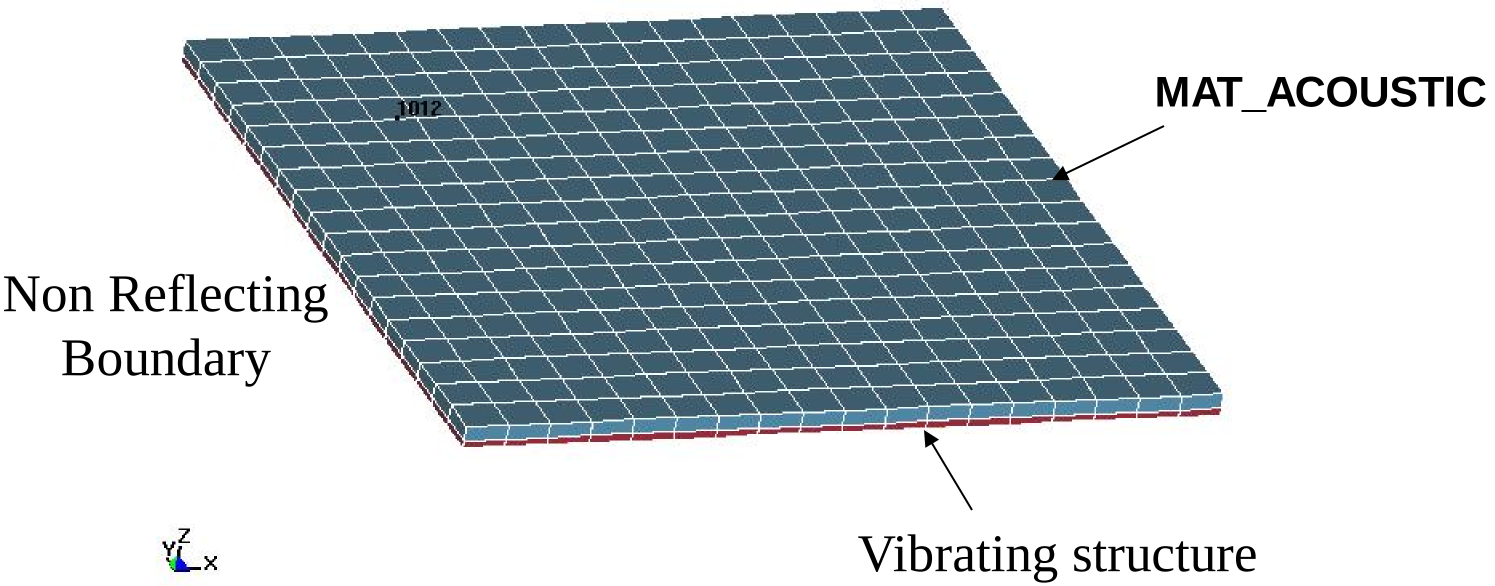
Full-coupling of fluid and structure

- A layer of acoustic fluid (***MAT_ACOUSTIC**) is added to the surface of the vibrating structure
- Non reflecting boundary condition
- Both velocity and pressure are saved and converted to frequency domain
- Use velocity and pressure directly in the integral equation. No need to solve Ax=b

Helmholtz integral equation

$$P(\omega) = -\int_S \left(i\rho\omega v_n(\omega) G + p(\omega) \frac{\partial G}{\partial n} \right) ds$$

- For exterior problems only
- Good for water, air, or other light or heavy fluid
- Number of fluid layers has little influence on acoustic results.



FREQUENCY_DOMAIN_ACOUSTIC_BEM_*{OPTION}

Card 1	1	2	3	4	5	6	7	8
Variable	RO	C	FMIN	FMAX	NFREQ	DTOUT	TSTART	PREF
Type	F	F	F	F	I	F	F	F
Default	none	none	none	none	0	0	0	0

Card 2	1	2	3	4	5	6	7	8
Variable	NSIDEXT	TYPEXT	NSIDINT	TYPINT	FFTWIN	TRSLT	IPFILE	IUNITS
Type	I	I	I	I	I	I	I	I
Default	0	0	0	0	0	0	0	0

Card 3	1	2	3	4	5	6	7	8
Variable	METHOD	MAXIT	TOLITR	NDD	TOLLR	TOLFCT	IBDIM	NPG
Type	I	I	F	I	F	F	I	I
Default		100	10E-4	1	10E-6	10E-6	1000	2

Card 4	1	2	3	4	5	6	7	8
Variable		**NBC**	RESTRT	IEDGE	NOEL	NFRUP		
Type		I	I	I	I	I		
Default		1	0	0	0	0		

Card 5 is defined NBC times.

Card 5	1	2	3	4	5	6	7	8
Variable	SSID	SSTYPE	NORM	BEMTYP	LC1	LC2		
Type	I	I	I	I	I	I		
Default	0	0	0	0				

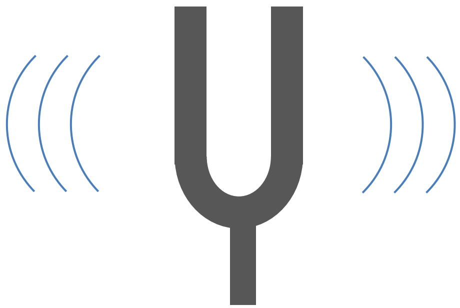
Additional Card 1 defined only for PANEL_CONTRIBUTION option.

Card 1	1	2	3	4	5	6	7	8
Variable	NSIDPC							
Type	I							
Default	0							

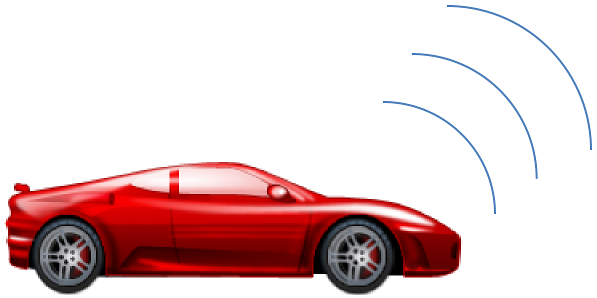
Additional Card 2 defined only for HALF_SPACE option.

Card 2	1	2	3	4	5	6	7	8
Variable	PID							
Type	I							
Default	0							

Vibro-Acoustic problems



Vibro-acoustics



Structure loading

↓ *FEM transient analysis*

SSD | V (P) in time domain | ← User data

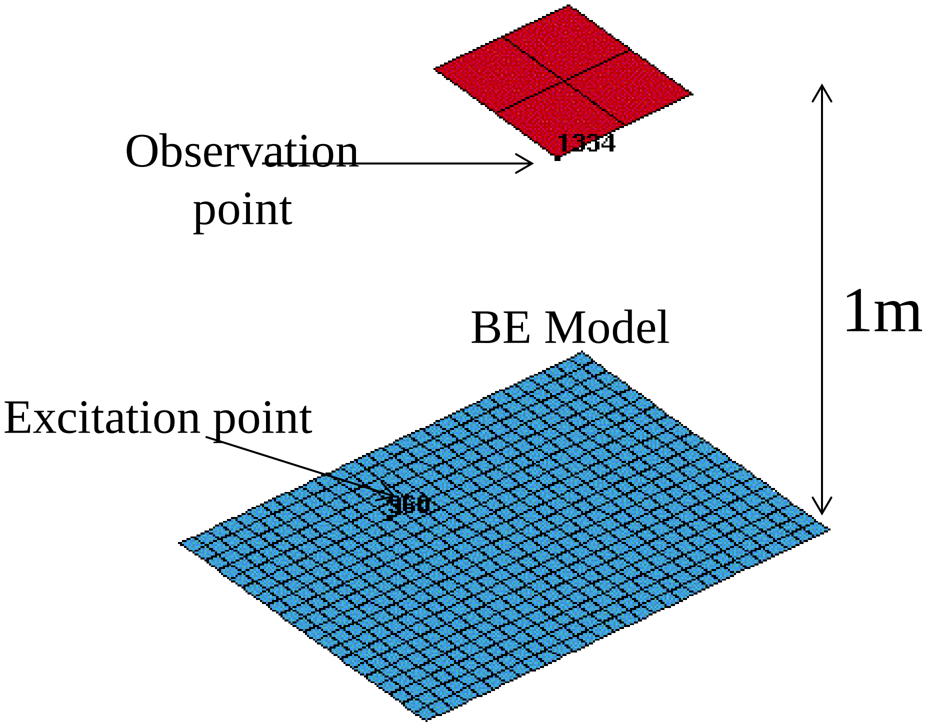
↓ *FFT*

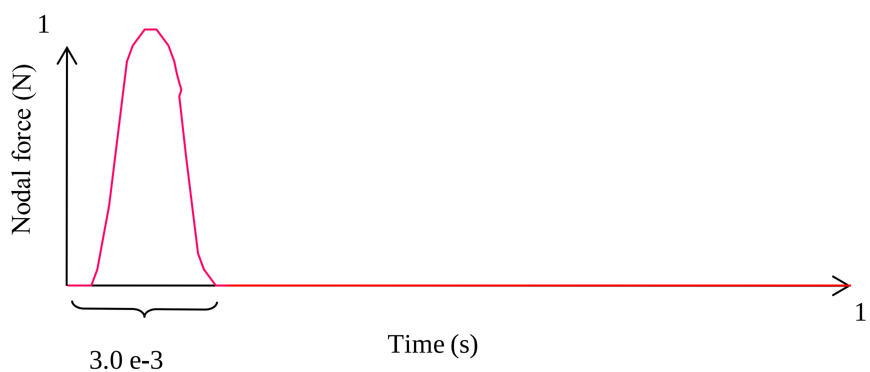
V (P) in frequency domain

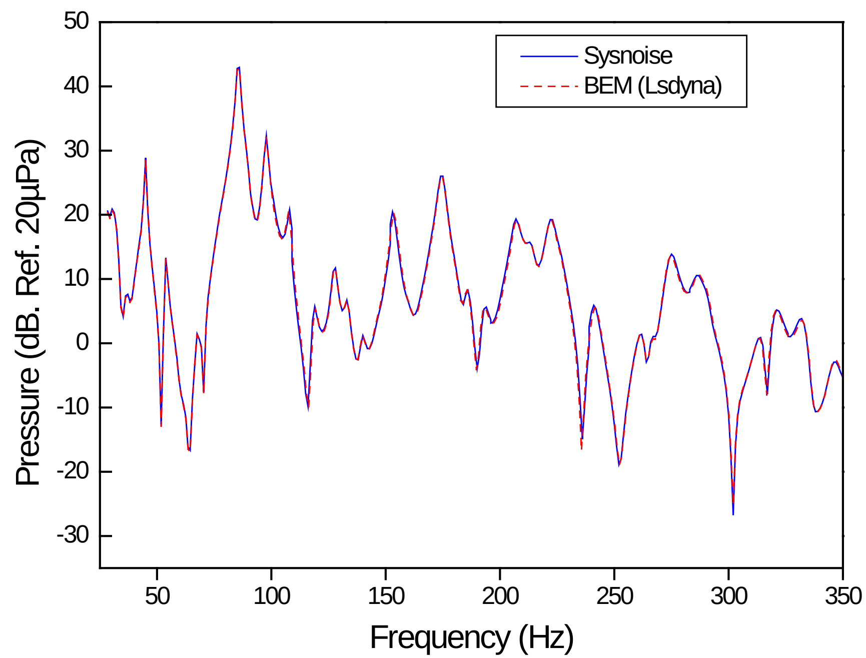
↓ *BEM acoustic analysis*

Acoustic pressure and SPL (dB) at field points

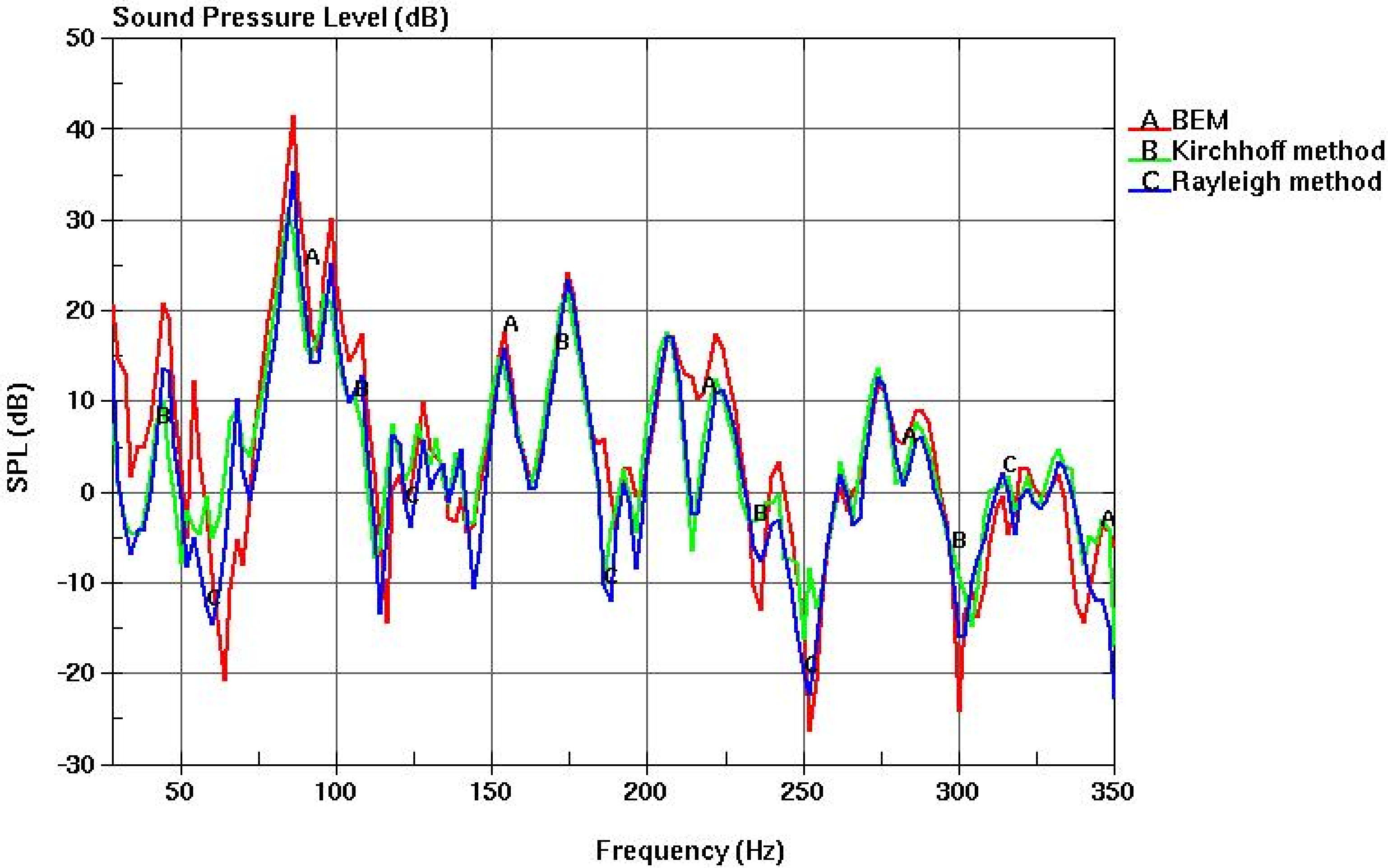
Example: a plate under excitation







Sysnoise result provided by ARUP


Sound Pressure Level (dB)
50
40
30
20
10
0
-10
-20
-30
SPL (dB)
50
100
150
200
250
300
350
Frequency (Hz)
A BEM
B Kirchhoff method
C Rayleigh method

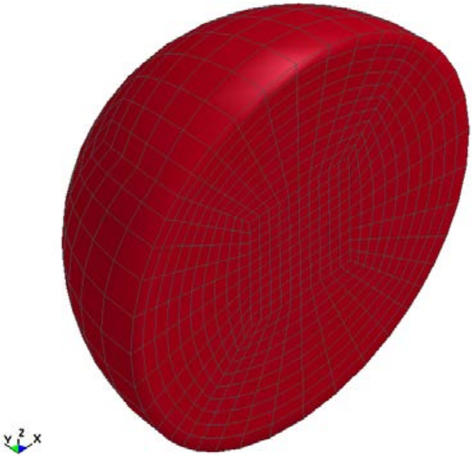
BEM vs. FEM

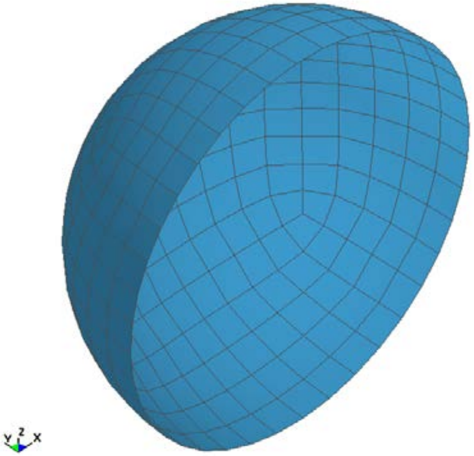
Advantages of BEM over other numerical methods (e.g. FEM)

- Only the boundary of the acoustic domain needs to be discretized
- The sommerfeld radiation condition is automatically satisfied so that the exterior domain need not be bounded

Disadvantages

- The matrix is fully populated
- The matrix needs to be reformed at each individual frequency
- Limited to homogeneous media

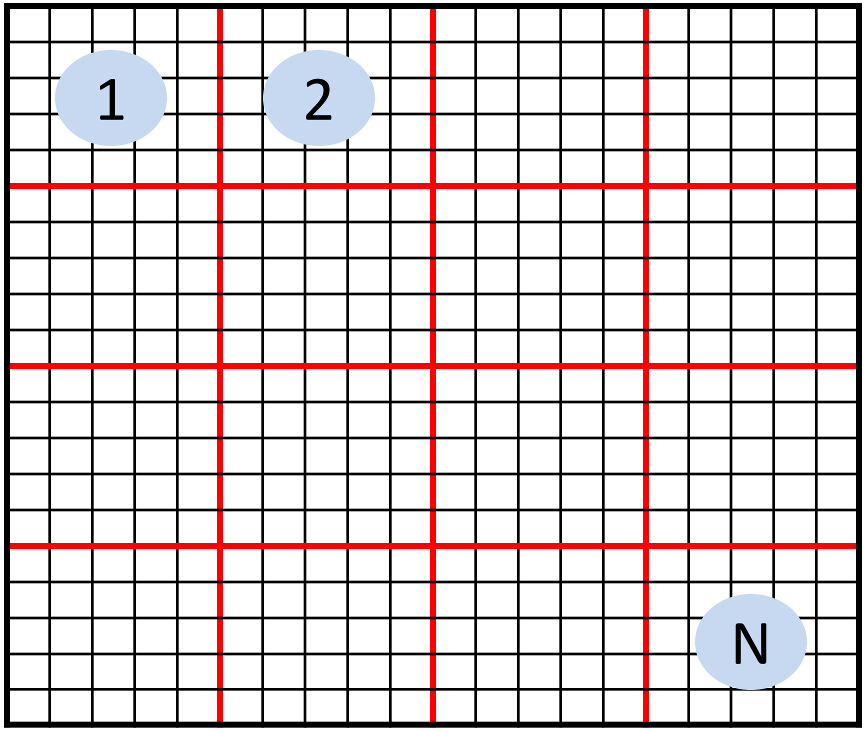




Fast BEM based on low rank approximation

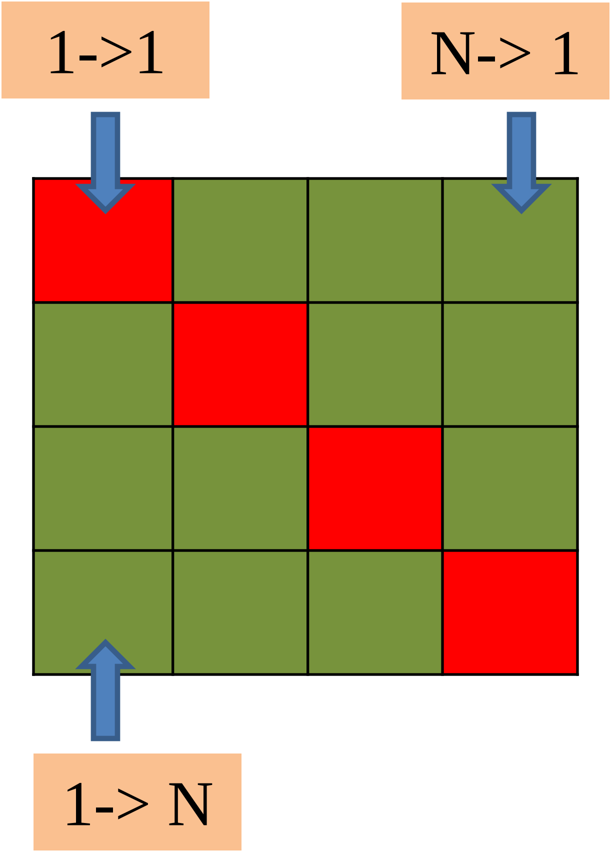
- Coupling with FEM in LS-DYNA
- Domain decomposition
- GMRES iterative solver
- Low Rank approximation
- Block diagonal preconditioning

Partitioning of domain



The whole domain for boundary elements

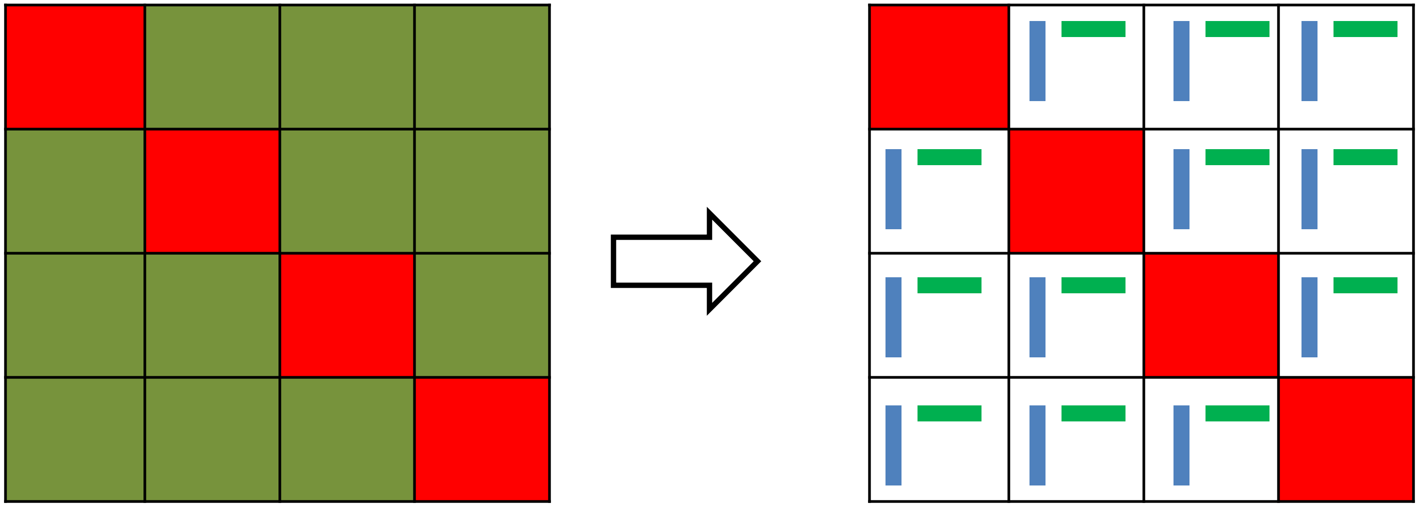
$$Ax = b$$



Low rank approximation of sub-matrix

$$A_{jk} \approx Q_{jk} R_{jk}$$

$$A_{jk} = \begin{bmatrix} a_{11} & & a_{1n} \\ & \ddots & \\ a_{m1} & & a_{mn} \end{bmatrix} \approx \begin{bmatrix} * & * \\ * & * \\ * & * \\ * & * \end{bmatrix}_{m\times r} \times \begin{bmatrix} * & * & * & * \\ * & * & * & * \end{bmatrix}_{r\times n}$$



The factorization stops when

$$\left|A_{jk}\right|_F - \left|R_{jk}\right|_F \le \delta_{jk} + \varepsilon \left|A_{jk}\right|_F \qquad \delta_{jk} = \varepsilon \left|A_{jj}\right|_F$$

Block diagonal preconditioner

$$Ax = b$$

$$[M + N]x = b$$

$$M^{-1}[M + N]x = M^{-1}b$$

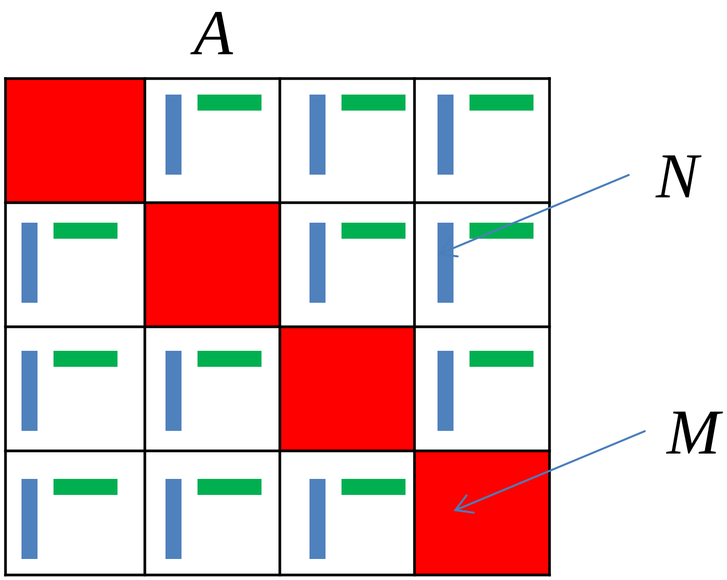
$$[I + M^{-1}N]x = M^{-1}b$$

$$x_{n+1} = [I + M^{-1}N]x_n$$

Step 1 $y = Nx_n$

Step 2 $Mz = y$

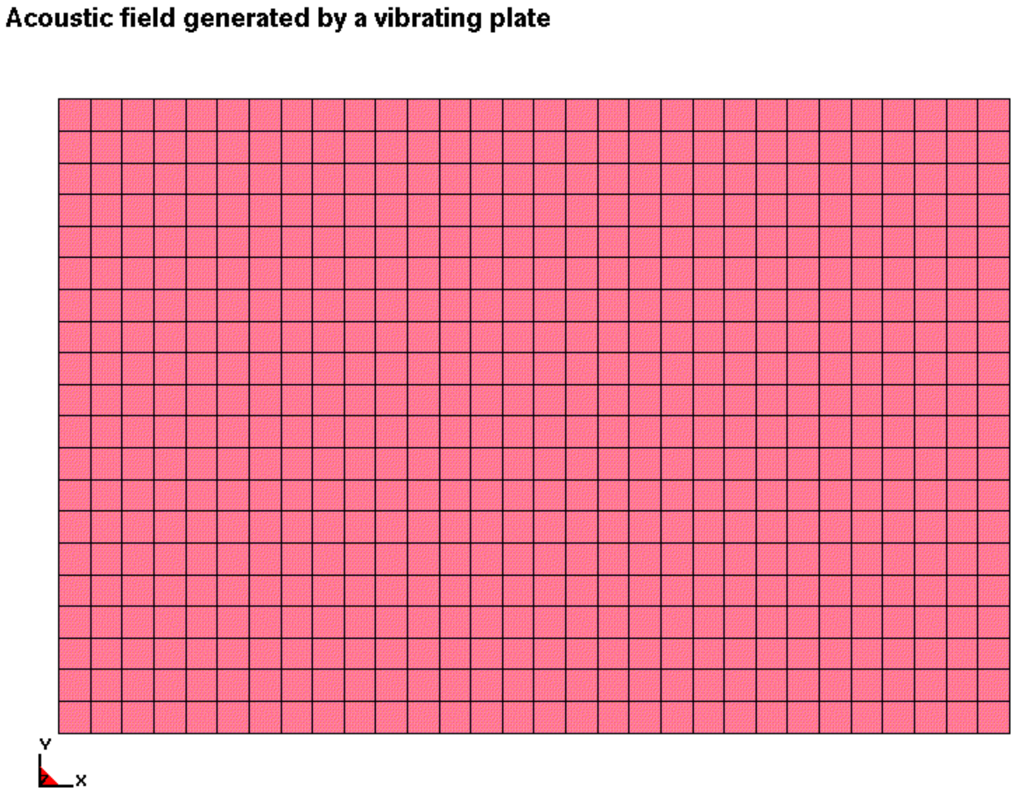
Step 3 $x_{n+1} = x_n + z$



$M = LL^T$ or $M = LU$

Comparing with $x_{n+1} = Ax_n$

Example: rectangular plate

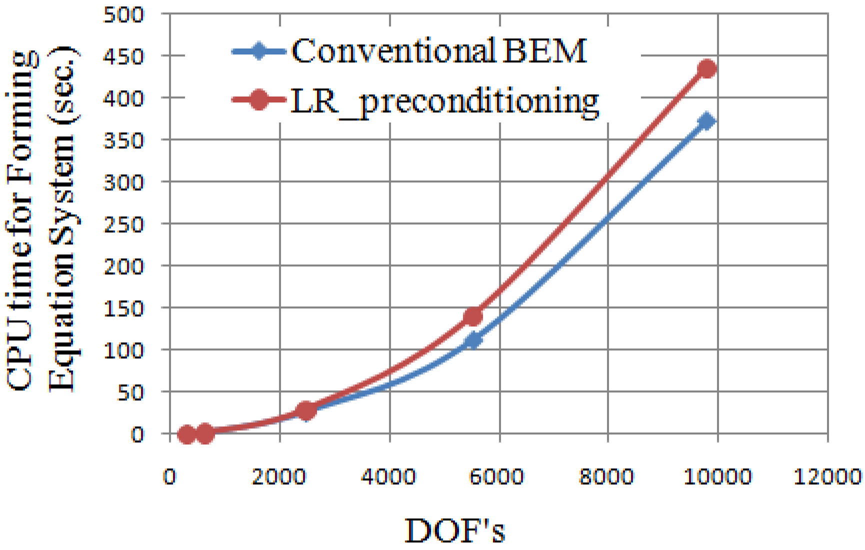


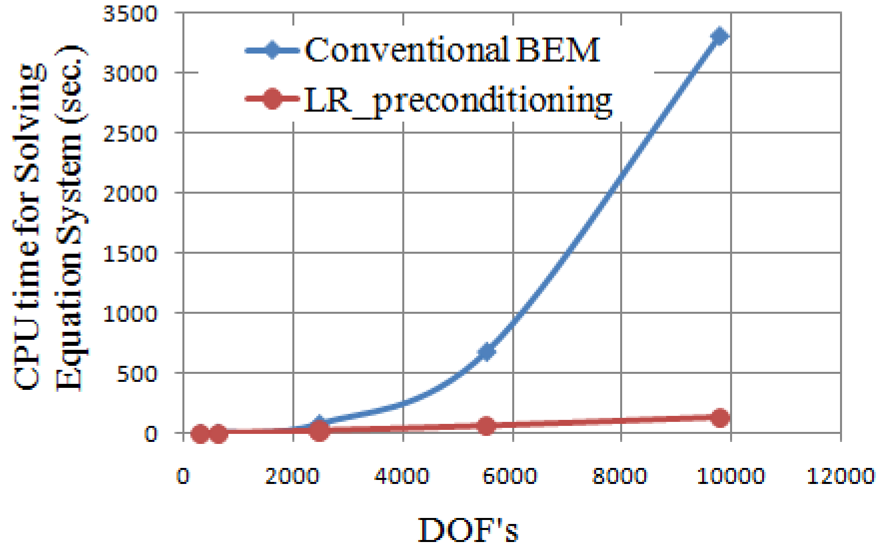
0.9 m by 0.6 m

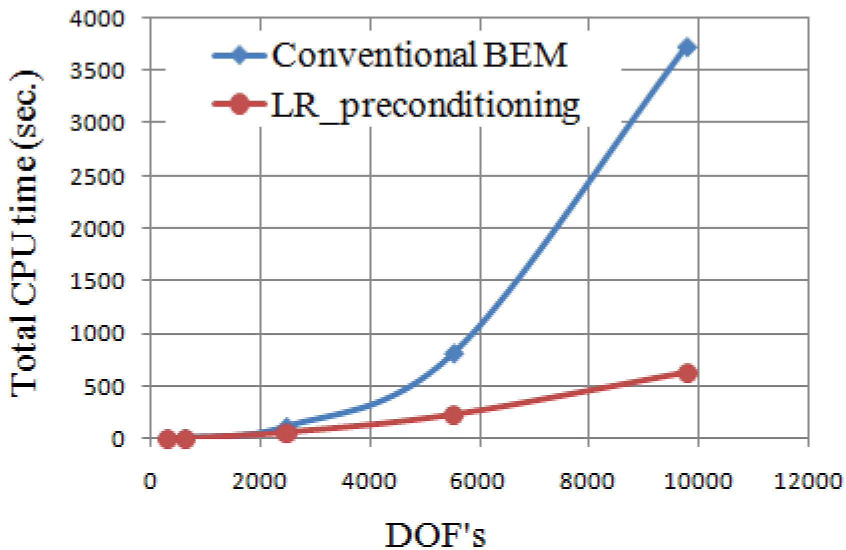
Excited by uniform harmonic velocity 1m /s at f=28 Hz

No. of DOF: 336; 651; 2501; 5551; 9801

CPU time







CPU time for the case of 9802 DOF (sec.)

	Forming E. S.	Solving E. S.	Total
Conventional	373	3302	3730
LR_preconditioning	498	110	667

Rank in the approximating matrices

For the case with 651 D.O.F. $N_{ij} \approx Q_{ij} R_{ij}$

Q

	1	2	3	4	5	6
1		88×23	160×21	88×5	77×3	150×4
2			160×19	88×23	77×5	150×7
3				88×7	77×4	150×21
4					77×23	150×20
5						150×19
6						

R

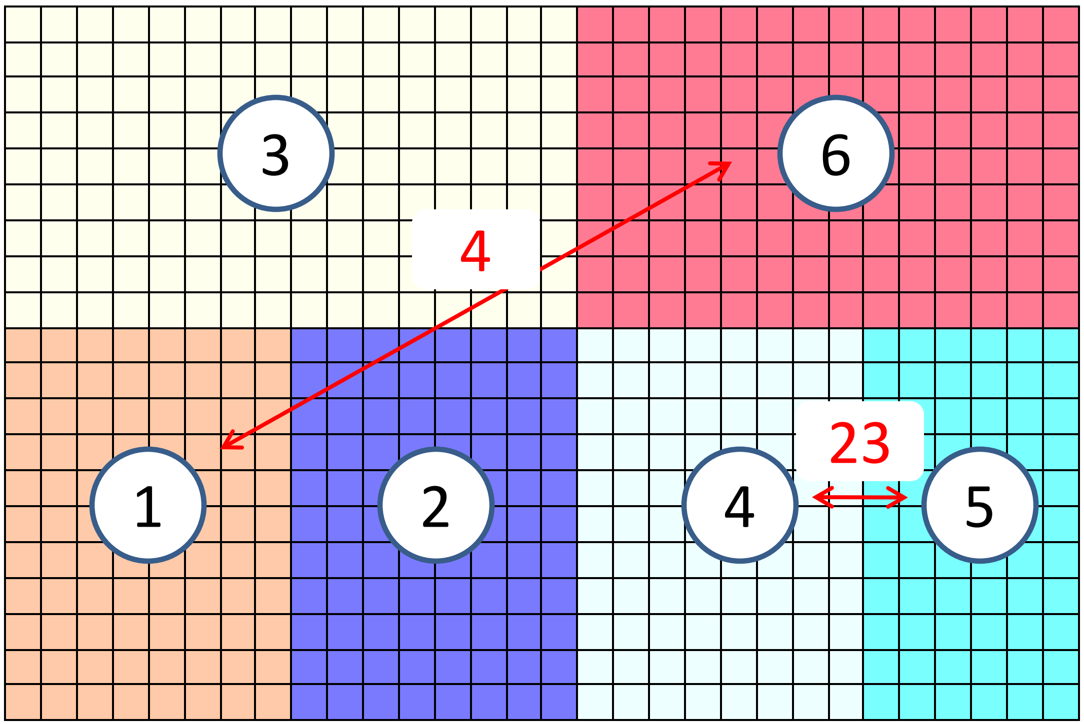
	1	2	3	4	5	6
1		23×88	21×88	5×88	3×88	4×88
2			19×88	23×88	5×88	7×88
3				7×160	4×160	21×160
4					23×88	20×88
5						19×77
6						

Entries in the LR approximating matrices: 167053

Entries in the full matrix: 651× 651= 423801

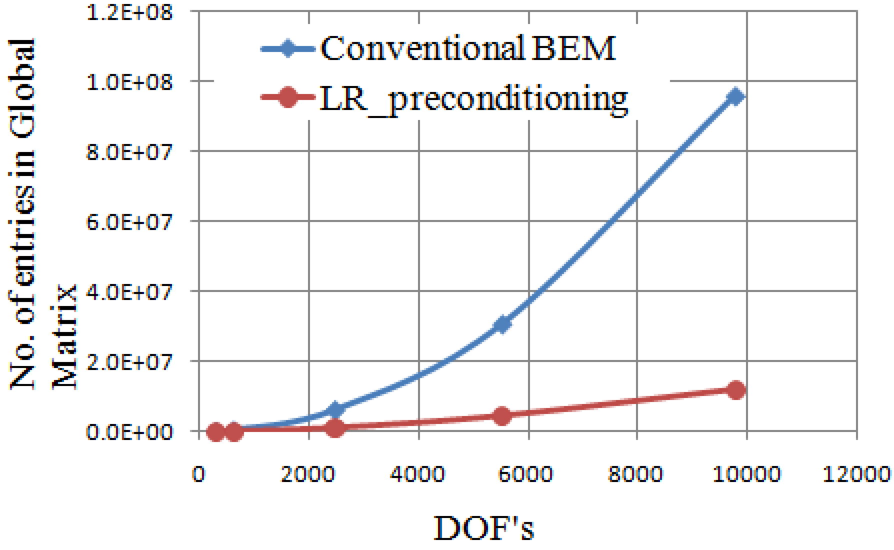
Total saving in Memory: 60.58%

What determines the rank in the approximating matrices?



Memory cost

Number of entries in matrix



Option: user provided velocity data

Card 4	1	2	3	4	5	6	7	8
Variable		NBC	RESTRT	IEDGE	NOEL	NFRUP		
Type		I	I	I	I	I		
Default		1	0	0	0	0		

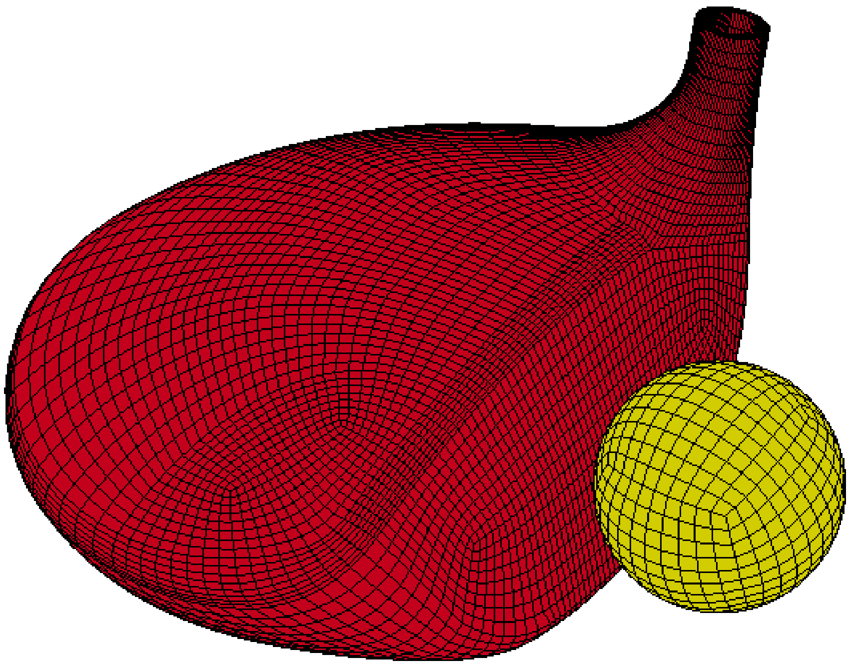
VARIABLE	DESCRIPTION
RESTRT	Restart options: EQ.0: LS-DYNA calculates the transient response and velocity history; EQ.1: LS-DYNA reads in velocity history saved in last run; EQ.2: Traditional LS-DYNA restart from d3dump file; EQ.3: LS-DYNA reads in user provided velocity history, saved in ASCII file “bevel”.

BEVEL ASCII file format:

The 1st line: number of nodes, 0 (for velocity) or 1 (for acceleration)
Then repeat the following for each time step:

```
----------------------------
" time=', time
NODE ID 1, vx, vy, vz
NODE ID 2, vx, vy, vz
...
NODE ID N, vx, vy, vz
 ----------------------------
```

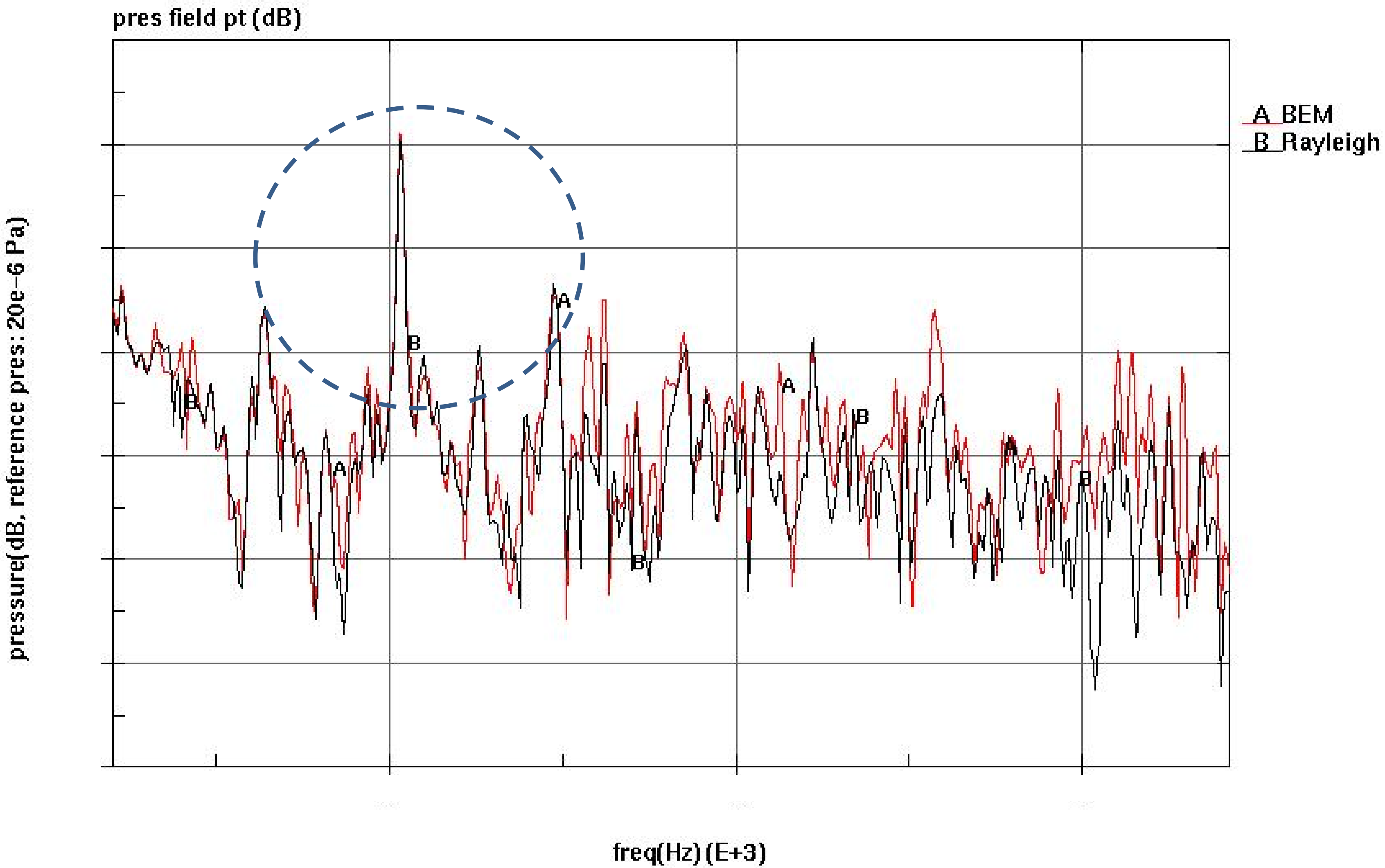
Example: golf club



Model information

FEM part
34412 Nodes
27616 Solid elements

BEM part
6313 Nodes
6272 Shell elements


pres field pt (dB)
A BEM
B Rayleigh
pressure(dB, reference pres: 20e−6 Pa)
freq(Hz) (E+3)

CPU cost

	Conventional	4 Sub-domains	32 sub-domains
Equation System	23136s	33296s	28514s
Iteration	67404s	8887.6s	1088.3s
Total	90556s (25 h 9 m)	55825s (15 h 30 m)	29618s (8 h 13 m)

Memory cost (for the 1st frequency)

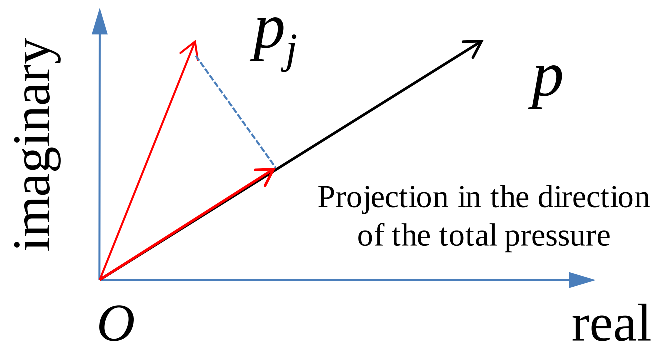
	Conventional	4 Sub-domains	32 sub-domains
No. of entries	39853969	13221015	3534811
Percentage	100%	33.2%	8.9%

ε_1 =1.0E-4 in GMRES
ε_2 =1.0E-6 in Low rank approximation

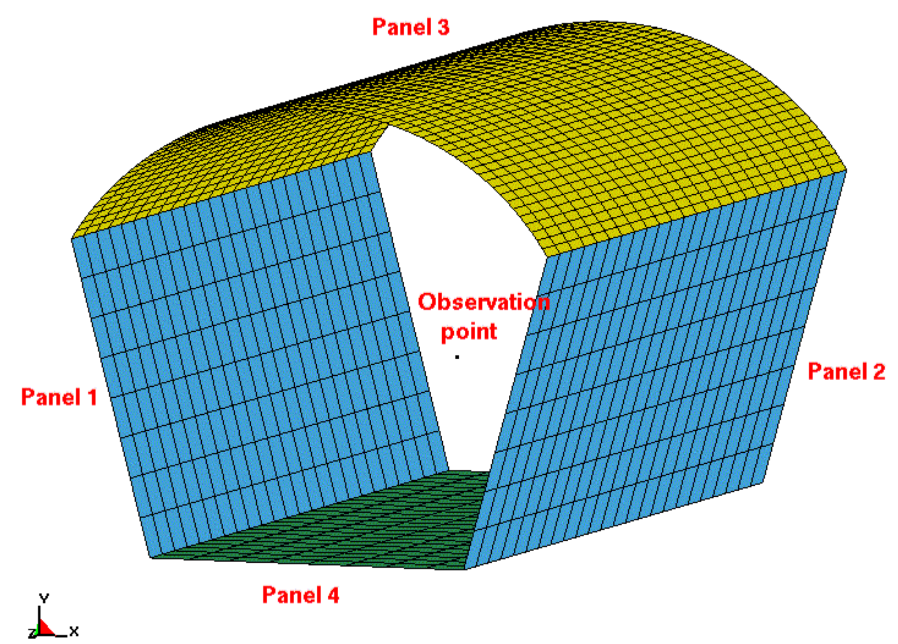
Acoustic Panel Contribution

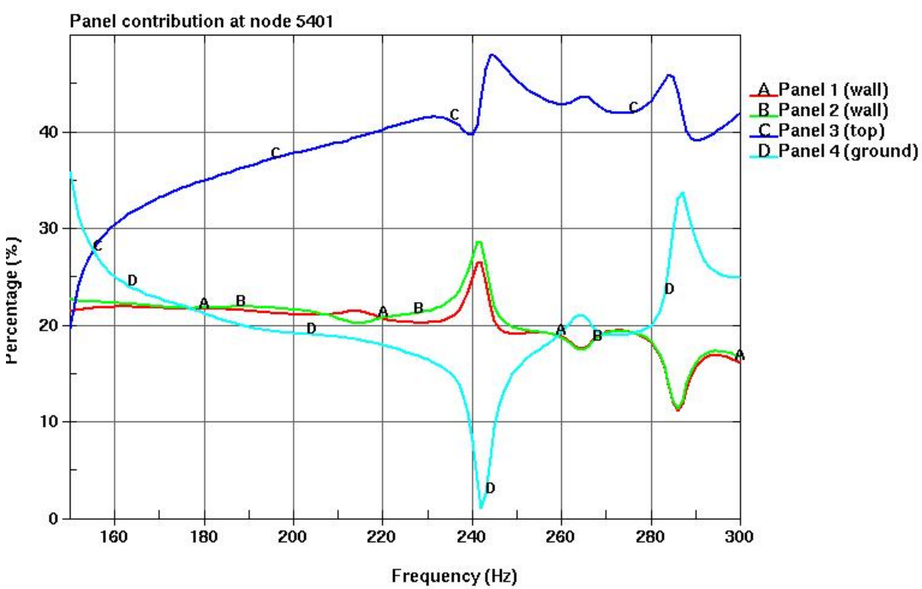
$$p(P)=\sum_{j=1}^{N}\int_{\Gamma_j}\left(G\frac{\partial p}{\partial n}-p\frac{\partial G}{\partial n}\right)d\,\Gamma_j$$

$$=\sum_{j=1}^{N}p_j(P)$$

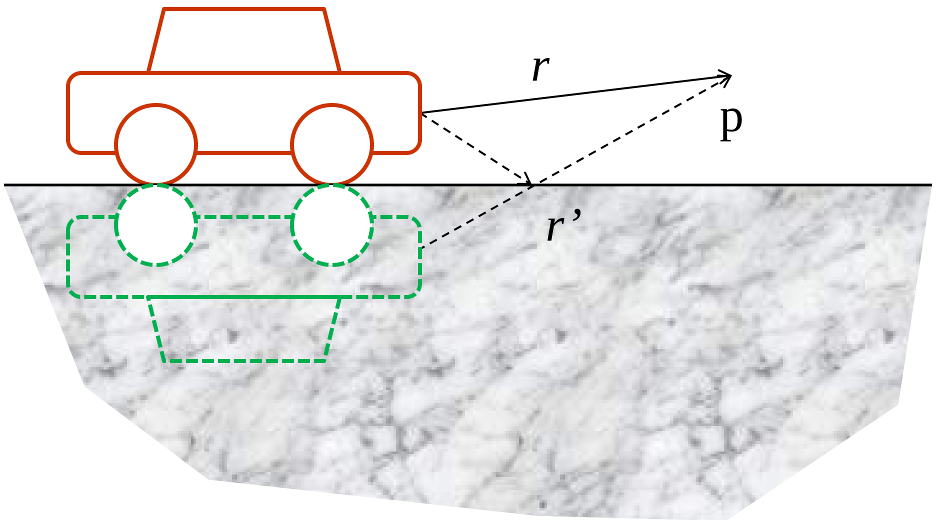


A simplified tunnel model





Half space problem



Free space Green's function

$$G = \frac{e^{-ikr}}{4\pi r}$$

Half space Green's function

$$G_H = \frac{e^{-ikr}}{4\pi r} + R_H \frac{e^{-ikr'}}{4\pi r'}$$

$R_H =$
- 1: rigid reflection plane, zero velocity
- -1: soft reflection plane, zero sound pressure (water-air interface in underwater acoustics)

Helmholtz integral equation

$$P(\omega) = -\int_S \left(i\rho\,\omega\, v_n(\omega) G_H + p(\omega) \frac{\partial G_H}{\partial n} \right) ds$$

The reflection plane is defined by *DEFINE_PLANE.

*DEFINE_PLANE

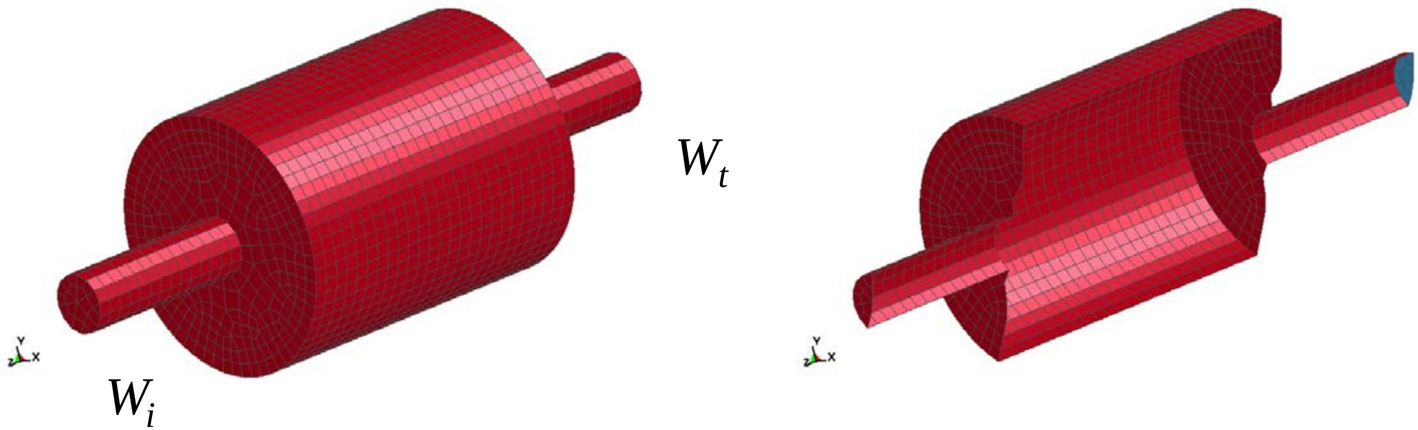
Purpose: Define a plane with three non-collinear points. The plane can be used to define a reflection boundary condition for problems like acoustics.

Card 1	1	2	3	4	5	6	7	8
Variable	PID	X1	Y1	Z1	X2	Y2	Z2	CID
Type	I	F	F	F	F	F	F	F
Default	0	0.0	0.0	0.0	0.0	0.0	0.0	0

Card 2	1	2	3	4	5	6	7	8
Variable	X3	Y3	Z3					
Type	F	F	F					
Default	0.0	0.0	0.0					

VARIABLE	DESCRIPTION
PID	Plane ID. A unique number has to be defined.
X1	X-coordinate of point 1.
…	
CID	Coordinate system ID applied to the coordinates used to define the current plane. The coordinates X1, Y1, Z1, X2, Y2, Z2, X3, Y3 and Z3 are defined with respect to the coordinate system CID.

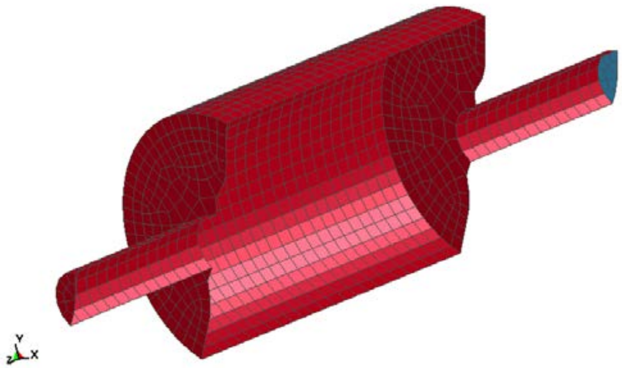
Example: muffler transmission loss analysis

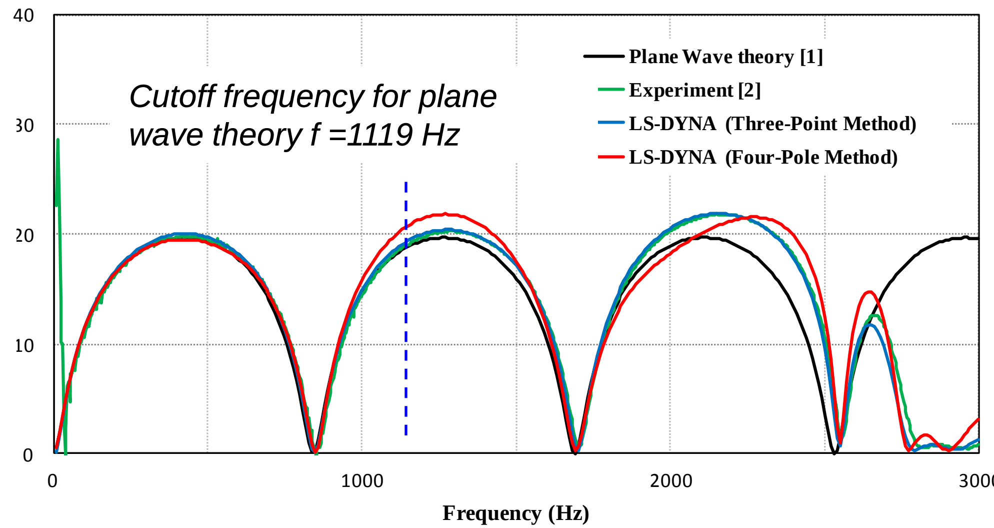


TL (Transmission loss) is the difference in the sound power level between the incident wave entering and the transmitted wave exiting the muffler when the muffler termination is anechoic (no reflection of sound).

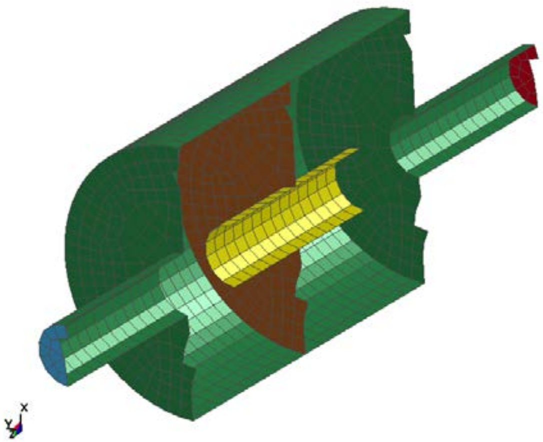
$$TL = 10 \log_{10} \frac{W_i}{W_t}$$

Simple expansion chamber





Double expansion chamber

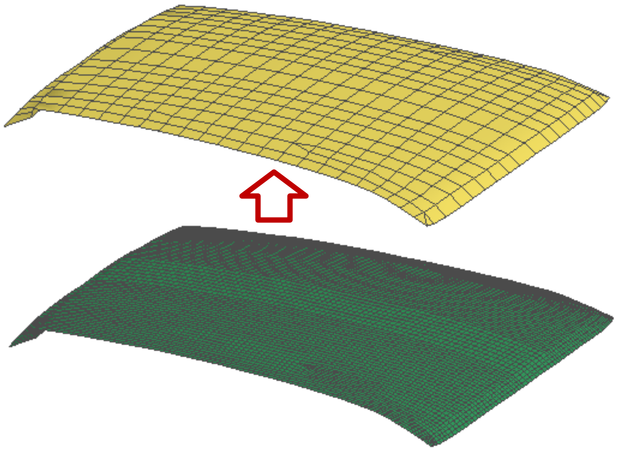


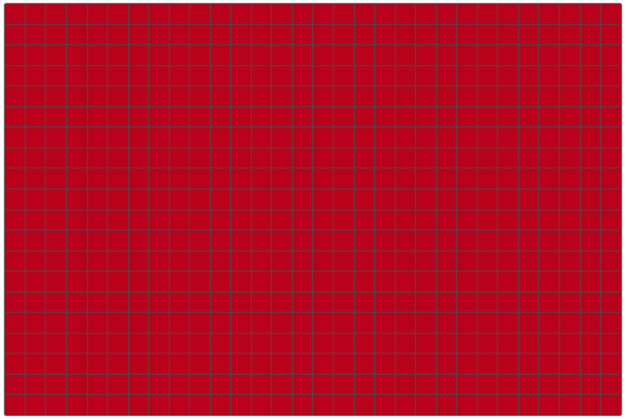
*BOUNDARY_ACOUSTIC_MAPPING

Purpose: Define a set of elements or segments on structure for mapping structural nodal velocity to boundary of acoustic volume.

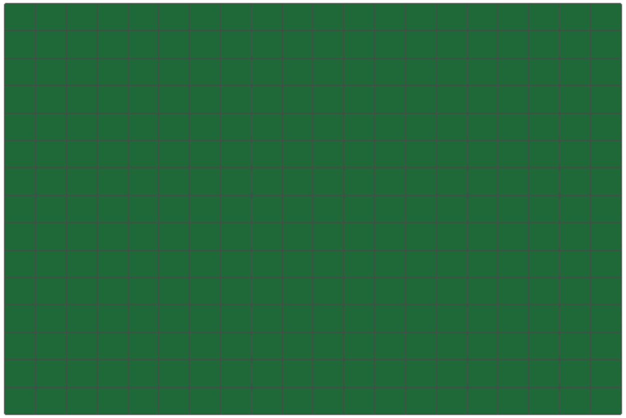
Card	1	2	3	4	5	6	7	8
Variable	SSID	STYP						
Type	I	I						
Default	none	0						

VARIABLE	DESCRIPTION
SSID	Set or part ID
STYP	Set type: EQ.0: part set ID, see *SET_PART, EQ.1: part ID, see *PART, EQ.2: segment set ID, see *SET_SEGMENT.

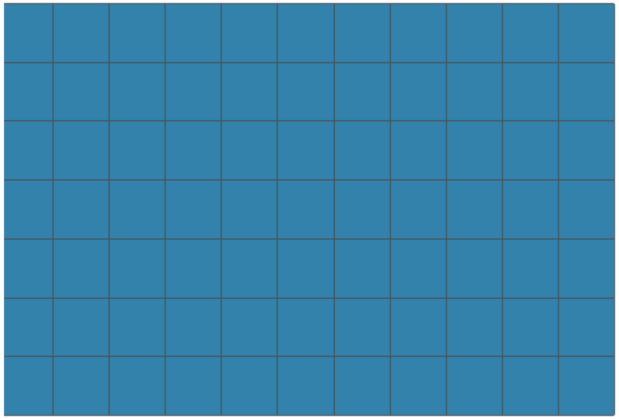




Mesh A: 20 × 30 (600)



Mesh B: 15 × 20 (300)

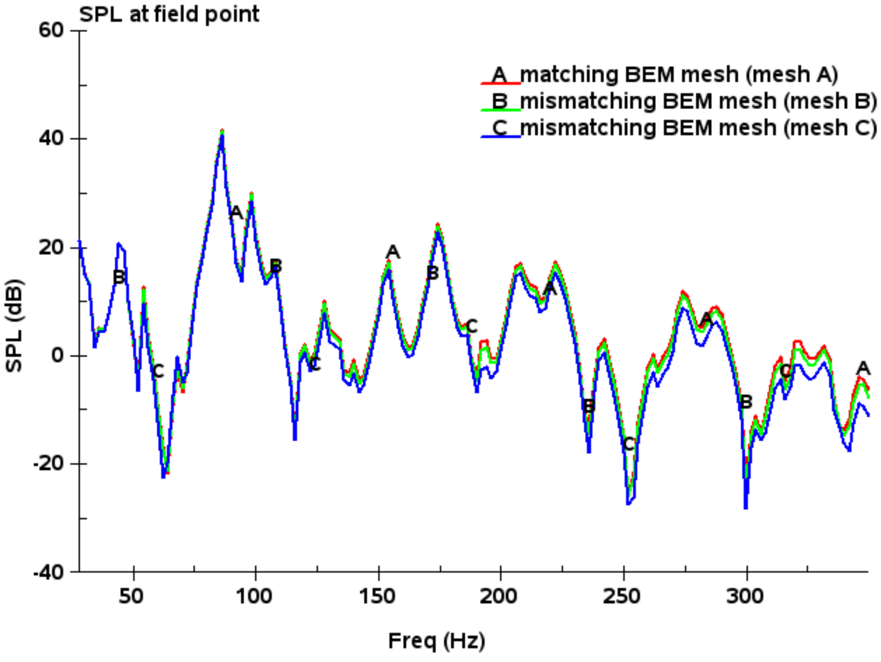


Mesh C: 7 × 11 (77)

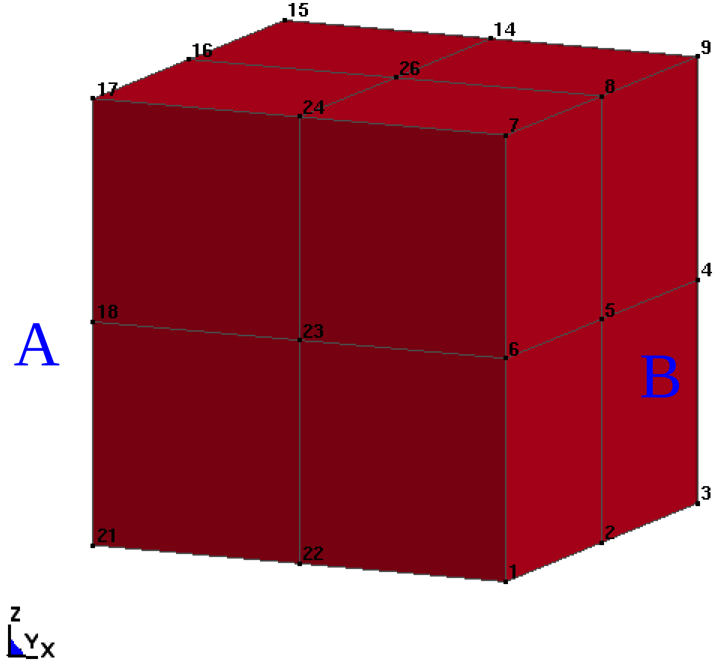
↓ *Original mesh for structure surface*

CPU time (Intel Xeon 1.6 GHz)

Mesh A	16 min 34 sec
Mesh B	10 min 10 sec
Mesh C	6 min 49 sec



Example: 1-D plane wave in a box



Size 1m × 1m × 1m

Boundary conditions

Face A: unit-amplitude normal velocity

Face B: characteristic impedance

$$p / v_n = \rho c$$

Other 4 Faces: rigid (normal velocity = 0)

Parameters

ρ = 1.21 kg/m^3, c = 343 m/s,

f = 5.45901 Hz (k =0.1)

Analytical solution $p = \rho c e^{-ikx}$

Sound pressure (Pa) at two field points in the box

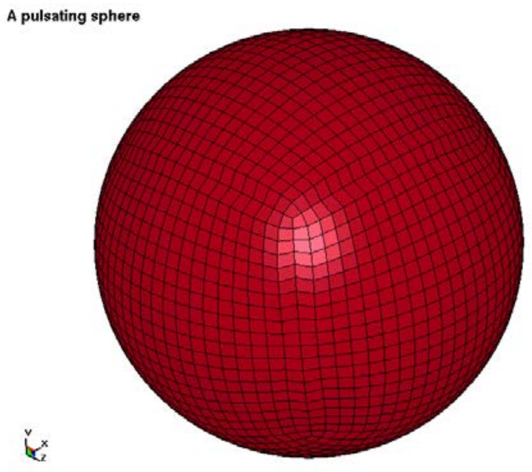
Field Point	Analytical Solution	BEM Solution
(0.25, 0.5, 0.5)	(414.9, -10.375)	(414.797, -9.217)
(0.5, 0.5, 0.5)	(414.511, -20.743)	(414.533, -19.585)

Reference: T. W. Wu (editor). Boundary Element Acoustics Fundamentals and Computer Codes, WIT press 2000.

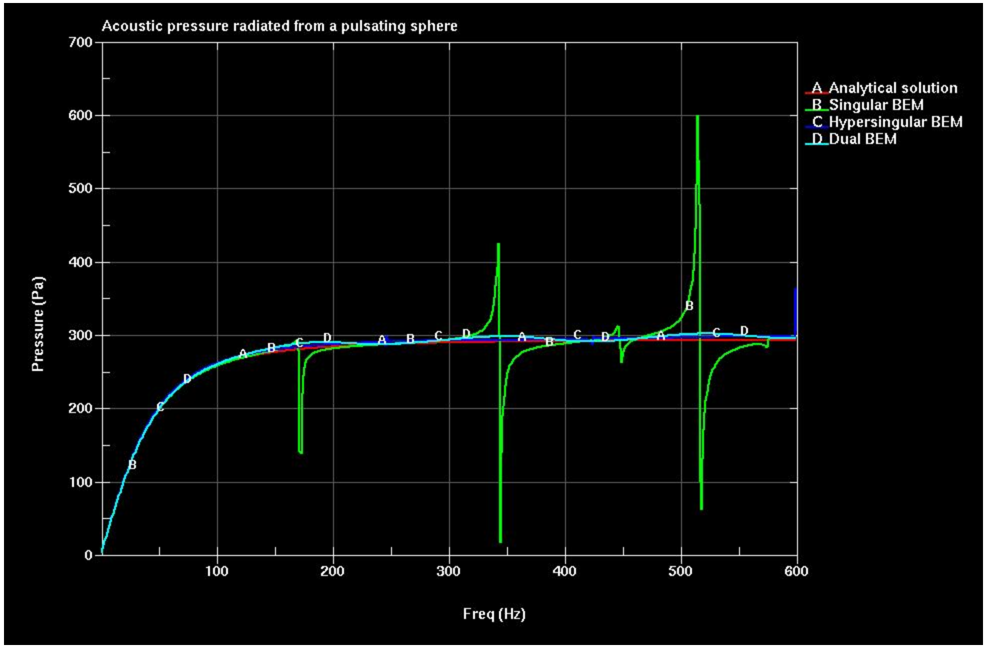
Burton-Miller dual BEM

Treatment for irregular frequency problem for exterior acoustic problems (conventional BEM fails to yield unique solution for exterior acoustic problems at the eigen-frequencies).

A constant collocation BEM based on Burton-Miller formulation has been implemented.



A pulsating sphere of a unit radius surrounded by air and excited by unit velocity for frequency 1-600 Hz

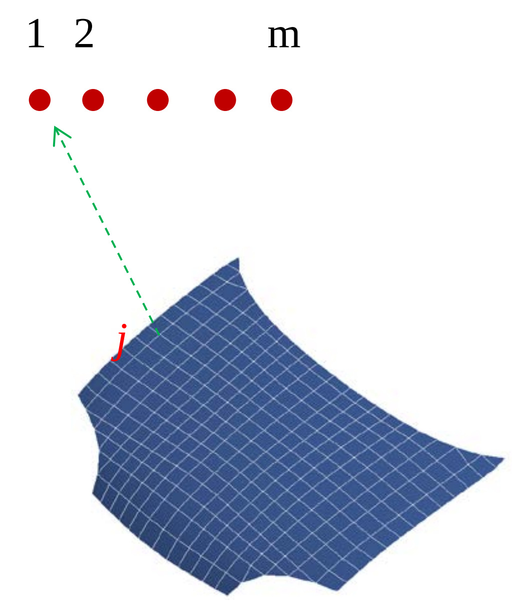


FREQUENCY_DOMAIN_ACOUSTIC_BEM_*ATV

- It calculates acoustic pressure (and sound pressure level) at field points due to unit normal velocity of each surface node.
- ATV is dependent on structure model, properties of acoustic fluid as well as location of field points.
- ATV is useful if the same structure needs to be studied under multiple load cases.

ATV at field points 1-m, due to unit normal velocity at node j

$$\begin{Bmatrix} P_1 \\ P_2 \\ \vdots \\ P_i \\ \vdots \\ P_m \end{Bmatrix} = \begin{bmatrix} \Omega_{1,1} & \Omega_{1,2} & \cdots & \Omega_{1,j} & \cdots & \Omega_{1,n} \\ \Omega_{2,1} & \Omega_{2,2} & \cdots & \Omega_{2,j} & \cdots & \Omega_{2,n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \Omega_{i,1} & \Omega_{i,2} & \cdots & \Omega_{i,j} & \cdots & \Omega_{i,n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \Omega_{m,1} & \Omega_{m,2} & \cdots & \Omega_{m,j} & \cdots & \Omega_{m,n} \end{bmatrix}_{m\times n} \begin{Bmatrix} V_1 \\ V_2 \\ \vdots \\ V_j \\ \vdots \\ V_n \end{Bmatrix}$$



Need to be computed only once

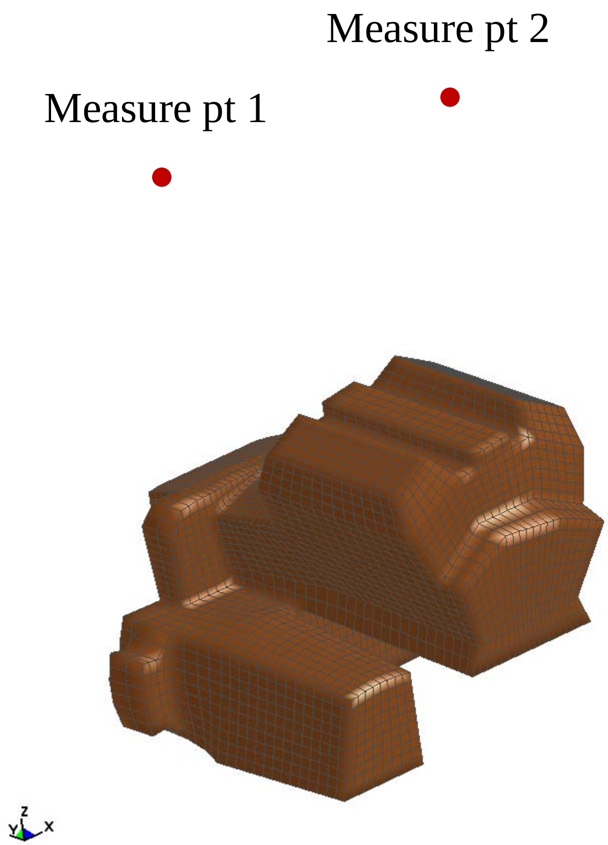
Change from case to case

LSTC Livermore Software Technology Corp.

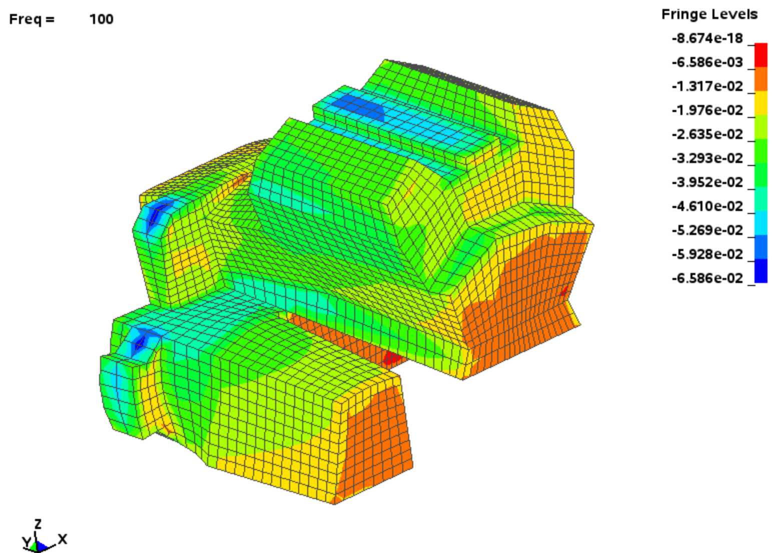
Example: Acoustic Transfer Vector

LS-DYNA

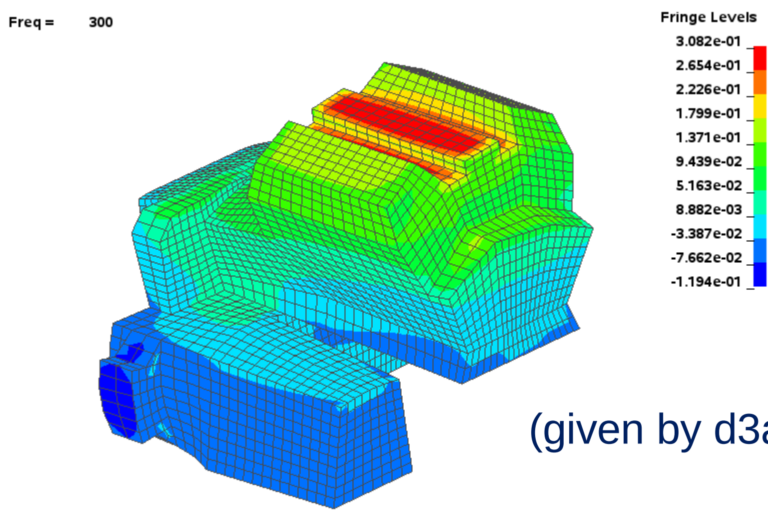
ATV of auto engine model



Real part of pressure ATV at pt 1



Imaginary part of pressure ATV at pt 2



(given by d3atv)

4.

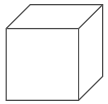
FREQUENCY DOMAIN FEM ACOUSTICS

Introduction: FEM Acoustics

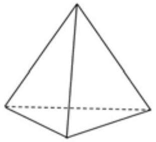
*FREQUENCY_DOMAIN_ACOUSTIC_FEM

1) An alternative method for acoustics. It helps predict and improve sound and noise performance of various systems. The FEM simulates the entire propagation volume -- being air or water.
2) Compute acoustic pressure and SPL (sound pressure level)
3) Output binary database: d3acs (accessible by LS-PREPOST)
4) Output ASCII database: Press_Pa and Press_dB as xyplot files
5) Output frequency range dependent on mesh size
6) Very fast since
   - ✓ One unknown per node
   - ✓ The majority of the matrix is unchanged for all frequencies
   - ✓ Using a fast sparse matrix iterative solver

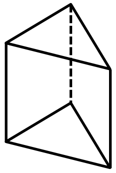
Hexahedron



Tetrahedron



Pentahedron



Brief theory

Helmholtz equation and boundary condition

$$\Delta p + k^2 p = 0 \qquad \Omega$$

$$\frac{\partial p}{\partial n} = -i\,\omega\,\rho\,v_n \qquad \Gamma$$

A Galerkin Finite Element Method for acoustics

$$\int_\Omega \Delta p \cdot N_i \, d\Omega + \int_\Omega k^2 \, p \cdot N_i d\Omega = 0$$

Where,

N_i is the shape function for node i.

*FREQUENCY_DOMAIN_ACOUSTIC_FEM

Card 1	1	2	3	4	5	6	7	8
Variable	RO	C	FMIN	FMAX	NFREQ	DTOUT	TSTART	PREF
Type	F	F	F	F	I	F	F	F
Default	none	none	none	none	0	0	0	0

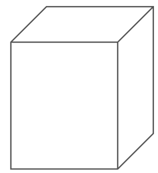
Card 2	1	2	3	4	5	6	7	8
Variable	PID	PTYP						
Type	I	I						
Default	none	0						

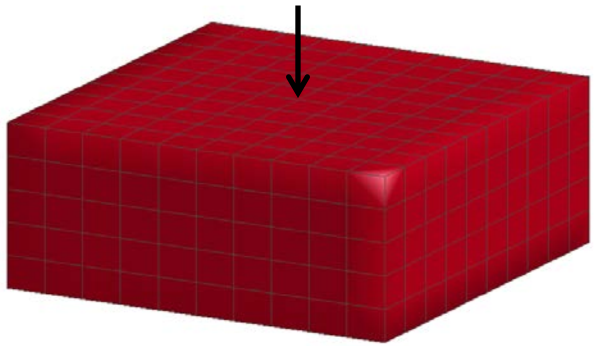
Card 3	1	2	3	4	5	6	7	8
Variable	SID	STYP	VAD	DOF	LCID1	LCID2	SF	VID
Type	I	I	I	I	I	I	F	I
Default	none	0	0	none	0	0	1.0	0

Card 4	1	2	3	4	5	6	7	8
Variable	NID	NTYP	IPFILE					
Type	I	I	I					
Default	none	0	0					

Example: box

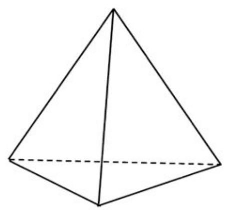
Hexahedron

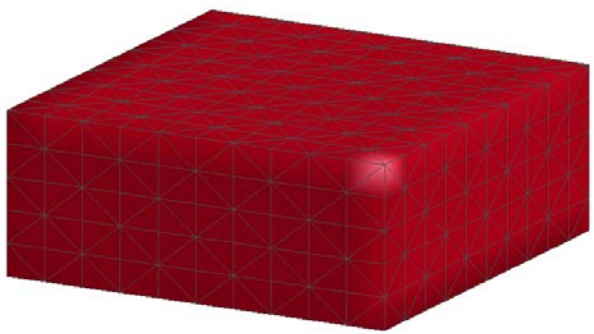




500 elements

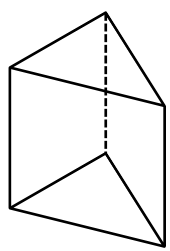
Tetrahedron

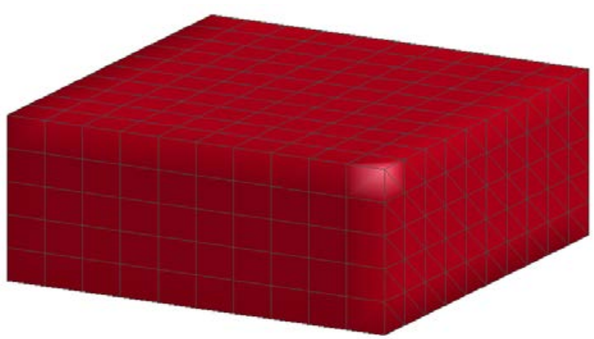




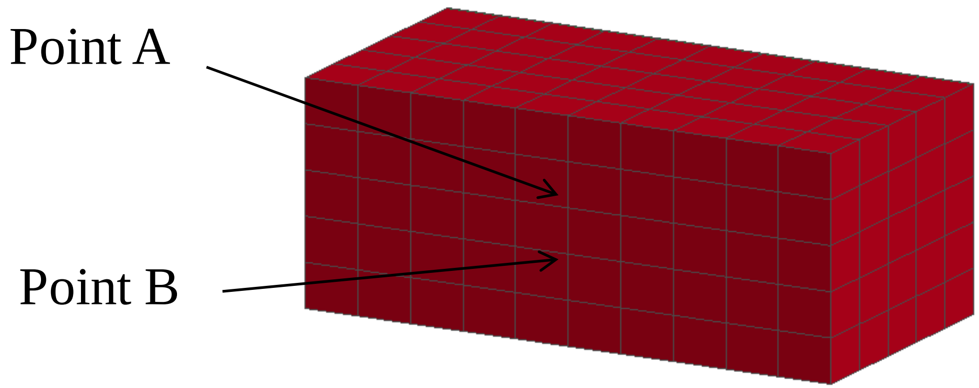
2500 elements

Pentahedron

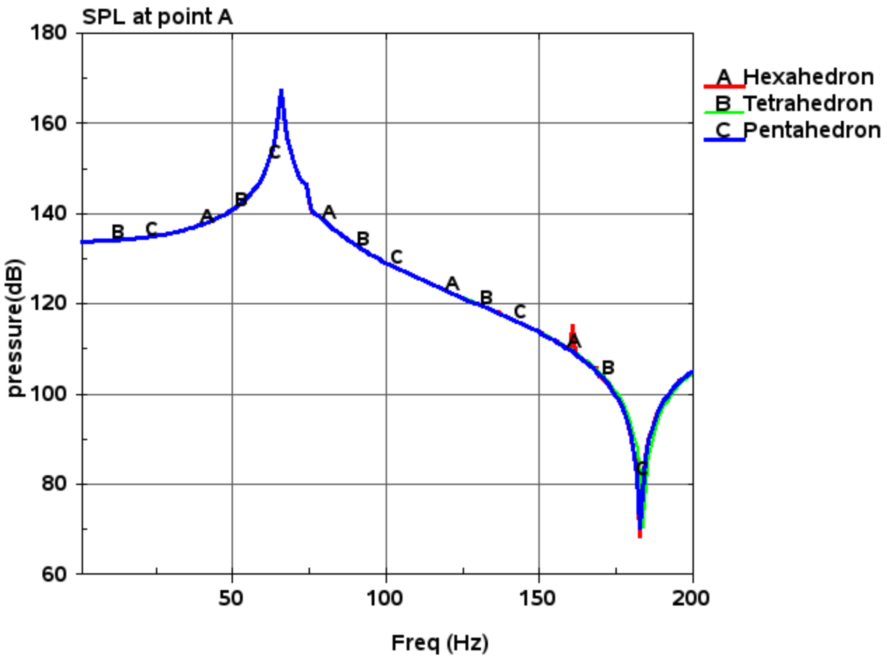




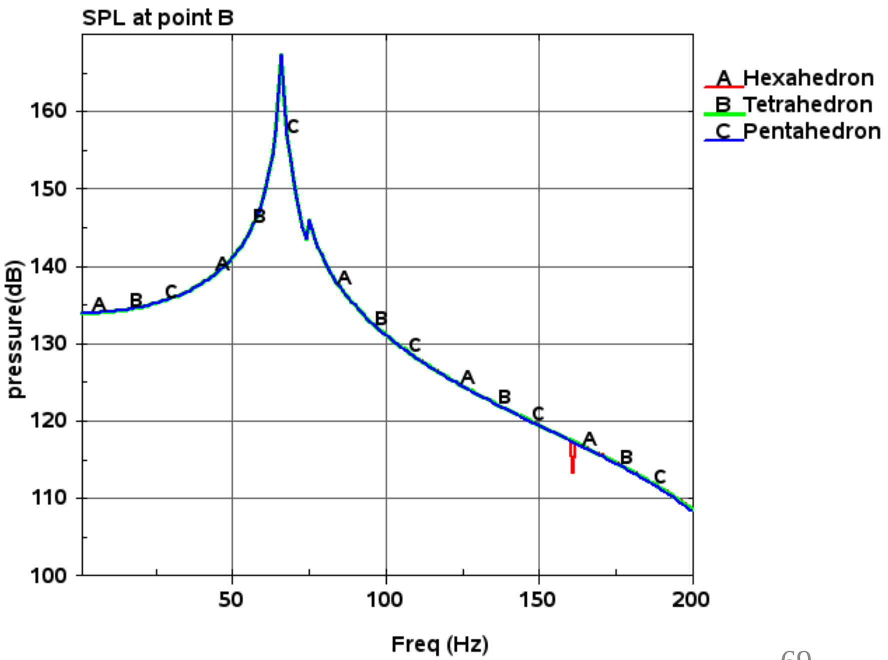
1000 elements



Point A
Point B



SPL at point A
pressure(dB)
Freq (Hz)
180
160
140
120
100
80
60
50
100
150
200
A Hexahedron
B Tetrahedron
C Pentahedron



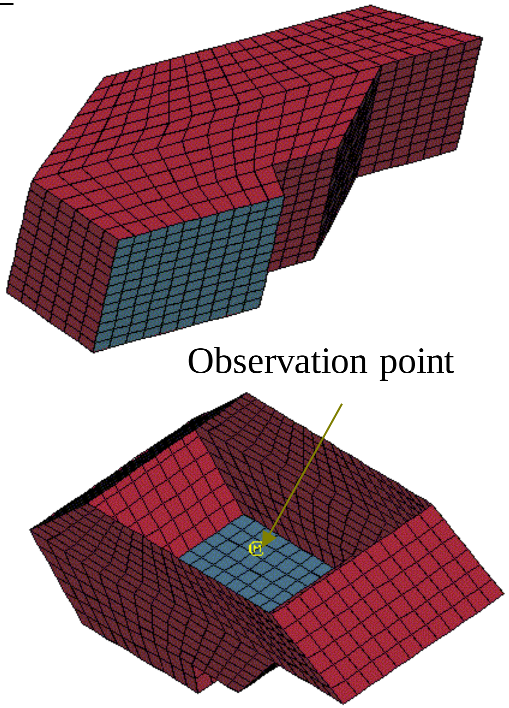
SPL at point B
pressure(dB)
Freq (Hz)
160
150
140
130
120
110
100
50
100
150
200
A Hexahedron
B Tetrahedron
C Pentahedron

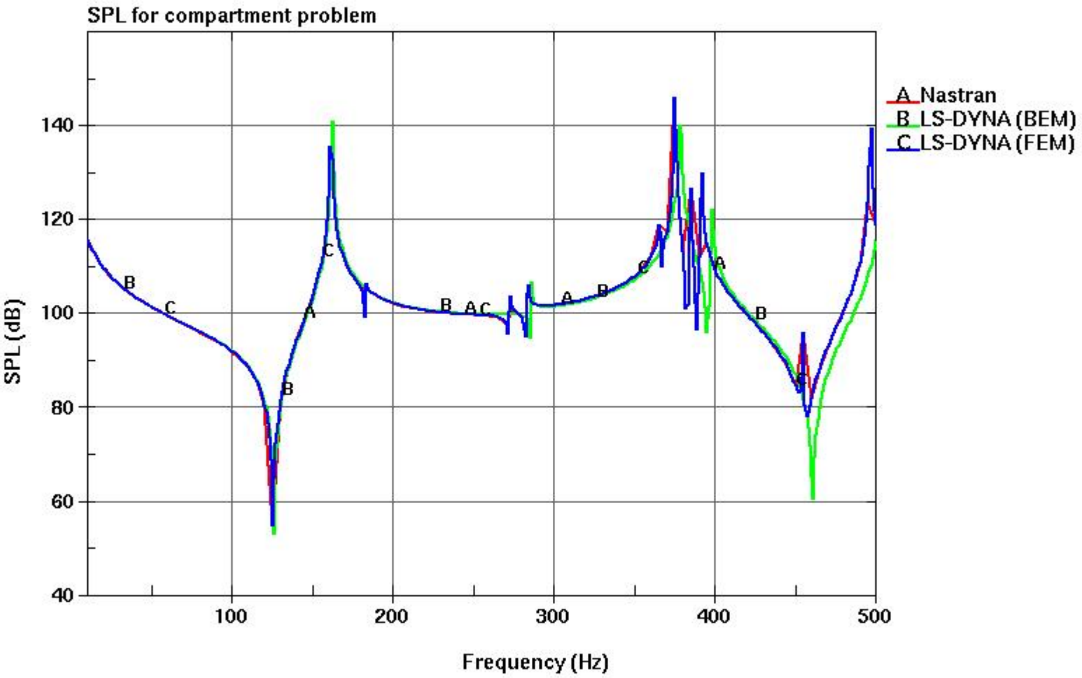
Example: compartment

Model information

FEM: 2688 elements

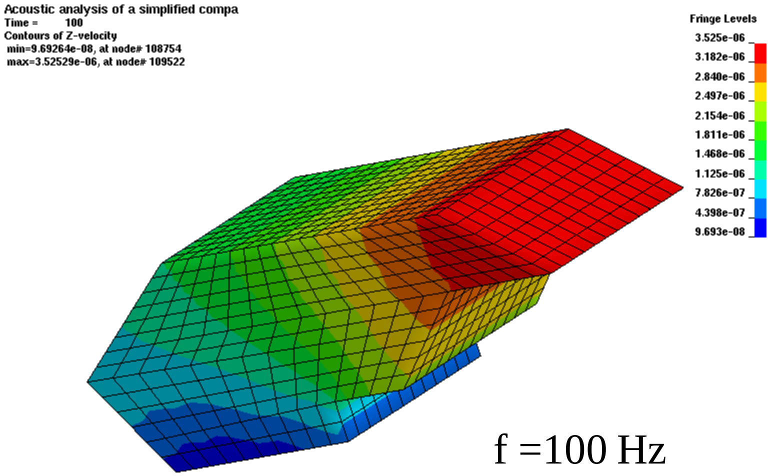
BEM: 1264 elements



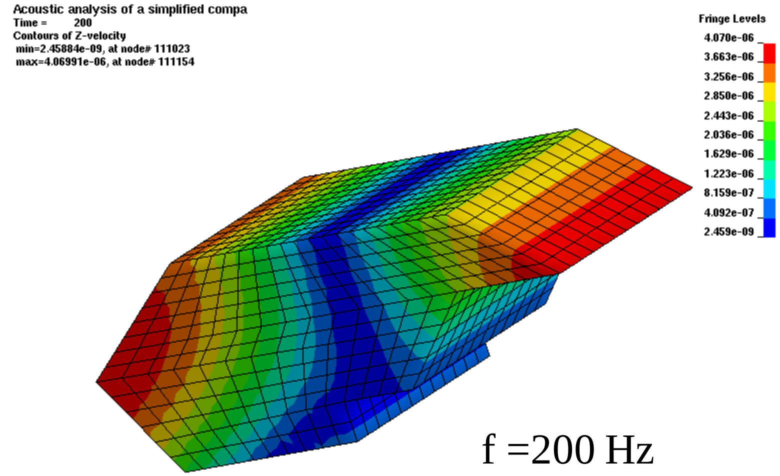


Excitation of the compartment (1.4×0.5×0.6) m^3
by a velocity of 7mm/s

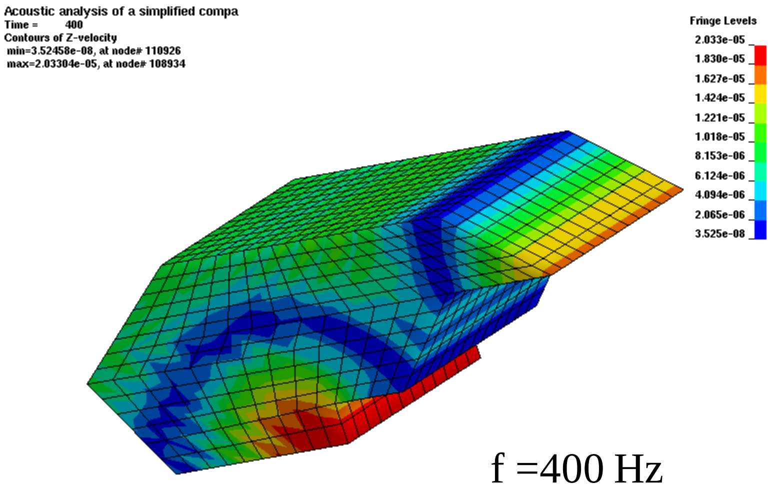
Pressure distribution



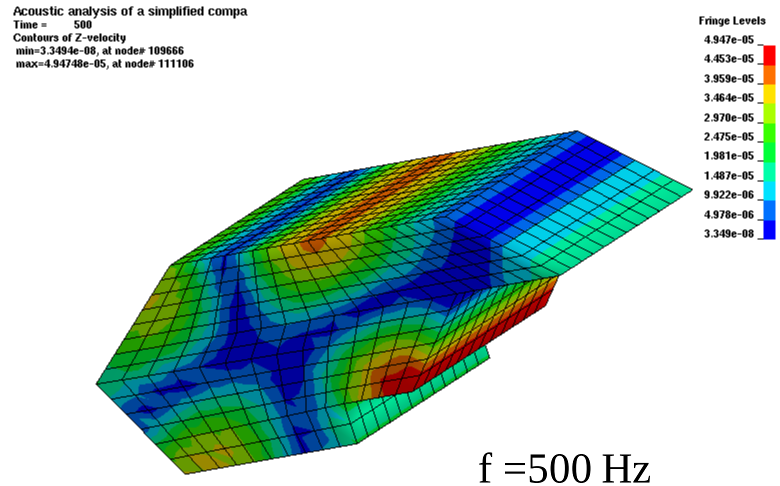
f =100 Hz



f =200 Hz



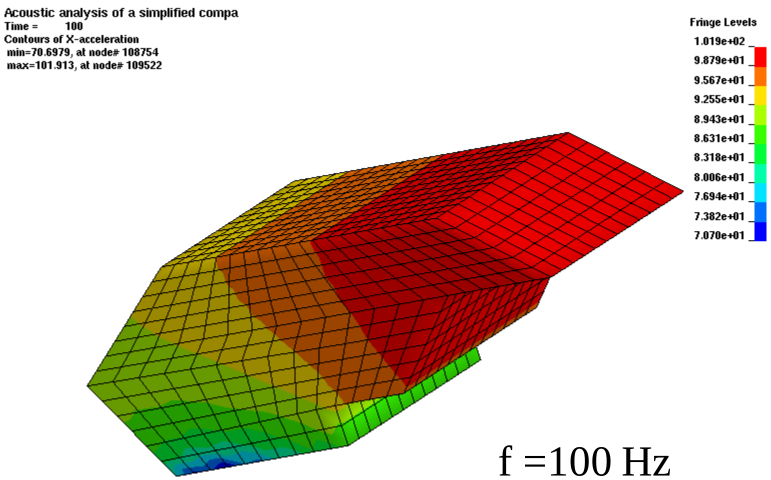
f =400 Hz



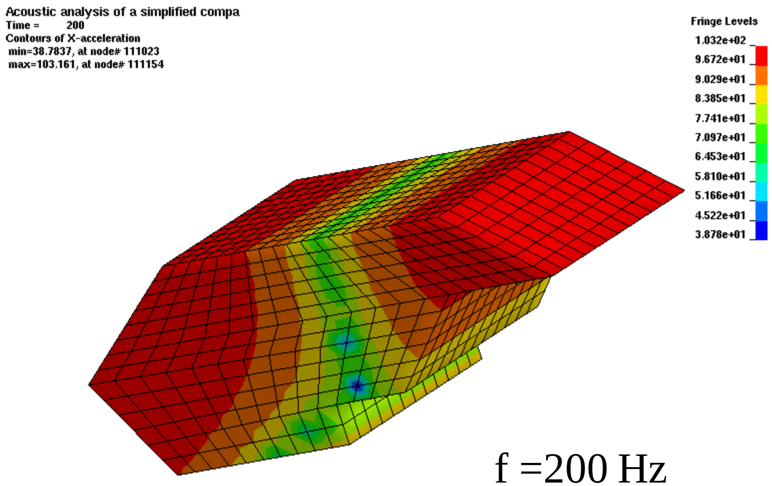
f =500 Hz

(given by d3acs)

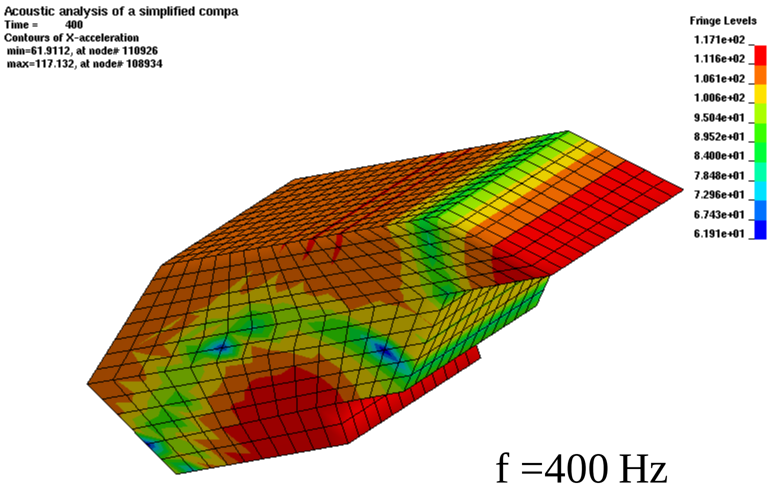
SPL distribution



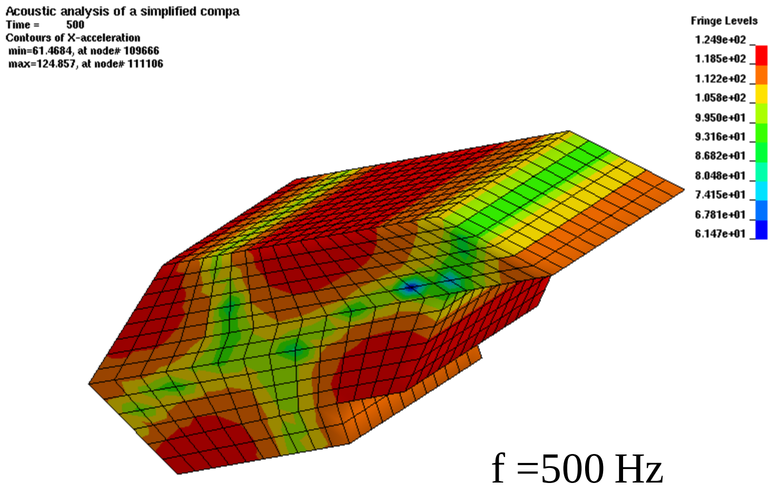
f =100 Hz



f =200 Hz



f =400 Hz



f =500 Hz

(given by d3acs)

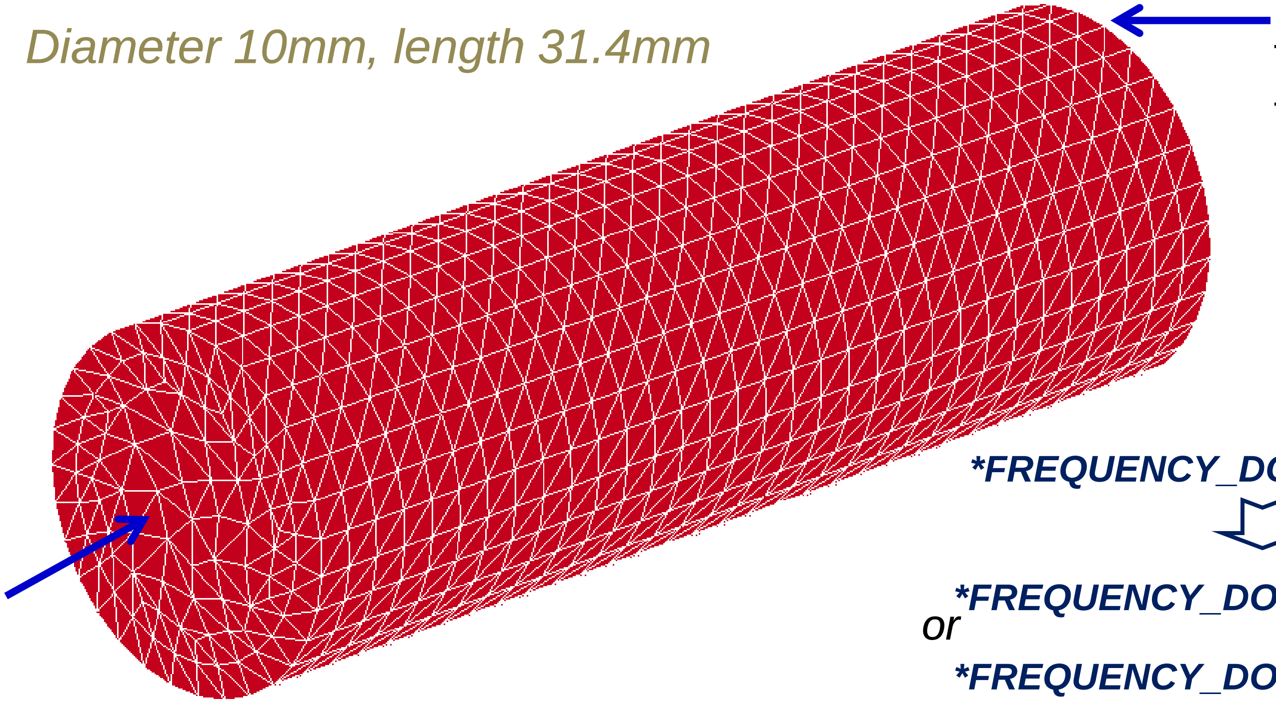
Example: cylinder

Introduction

To solve an interior acoustic problem by variational indirect BEM, collocation BEM and FEM. The cylinder duct is excited by harmonic nodal force at one end.

Diameter 10mm, length 31.4mm

This edge is fixed in x, y, z translation dof.



***FREQUENCY_DOMAIN_SSD**

⇩

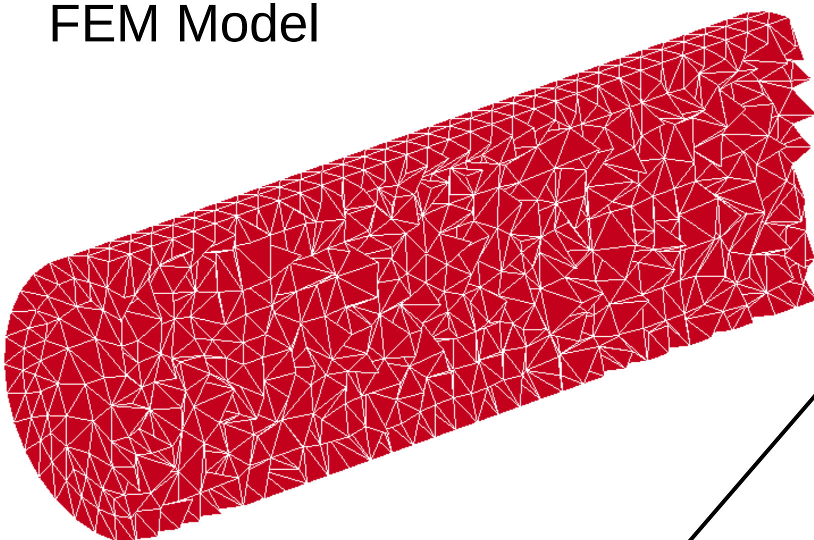
***FREQUENCY_DOMAIN_ACOUSTIC_BEM**

or

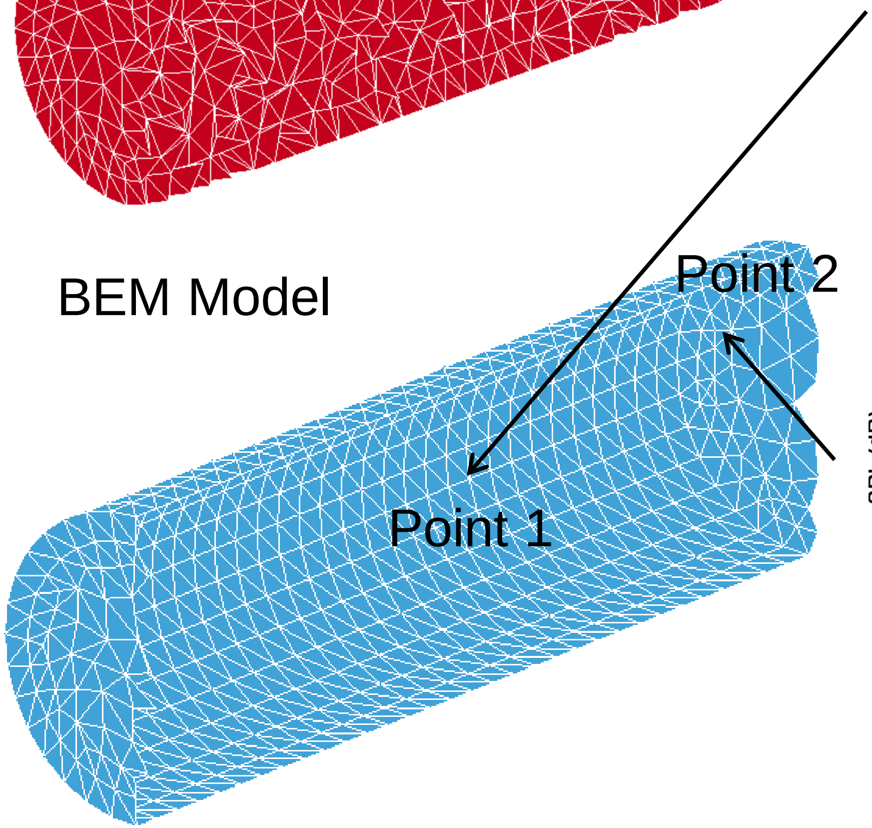
***FREQUENCY_DOMAIN_ACOUSTIC_FEM**

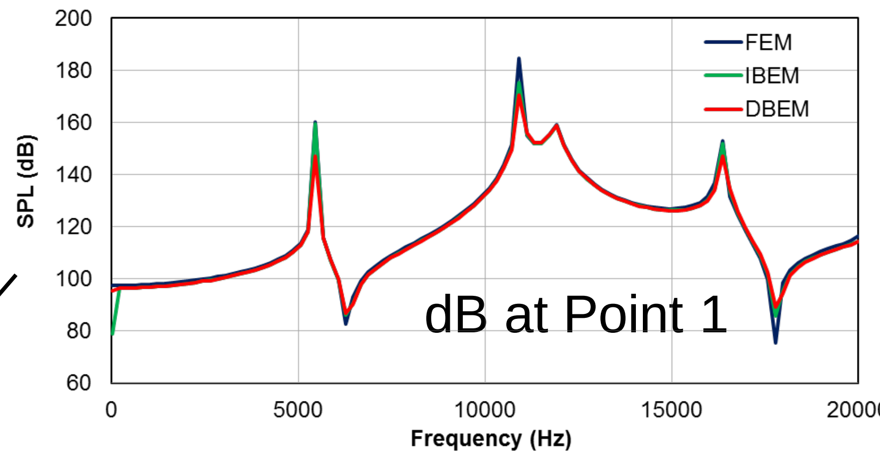
Nodal force 0.01N is applied for frequency range of 10-20000 Hz.

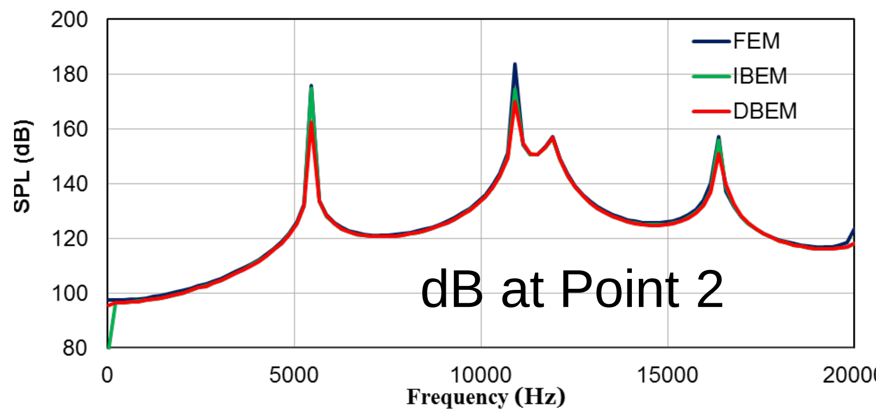
FEM Model



BEM Model

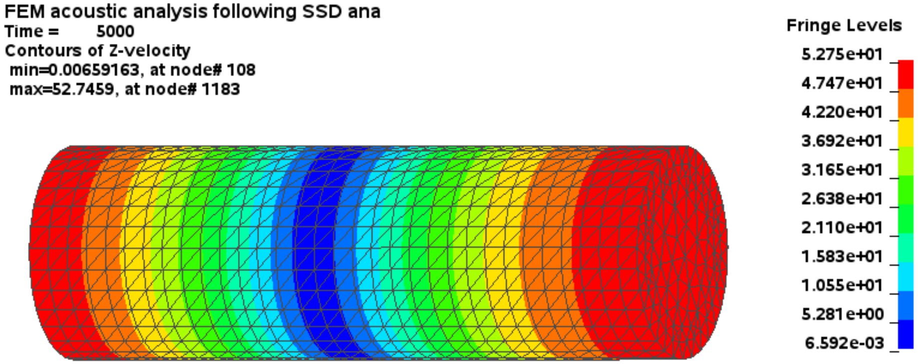




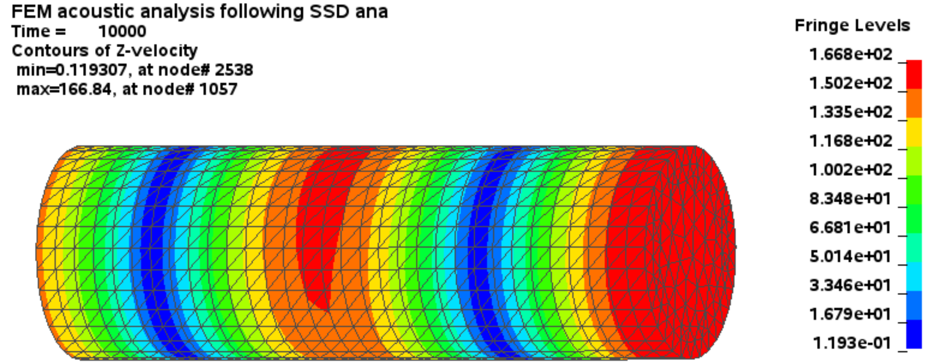


Acoustic pressure distribution

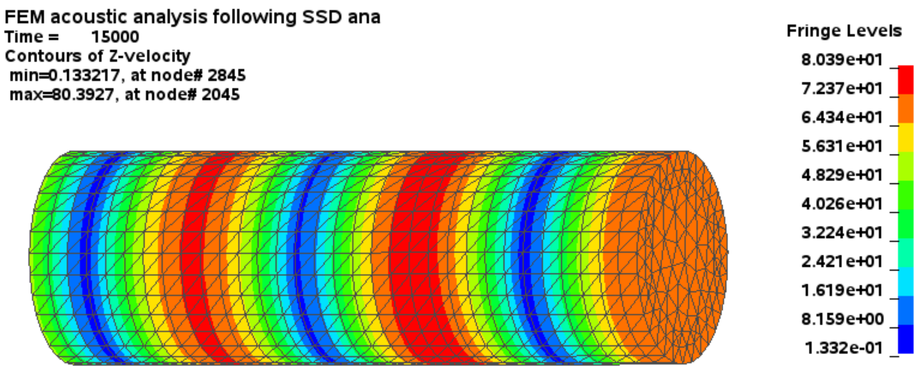
(given by d3acs)



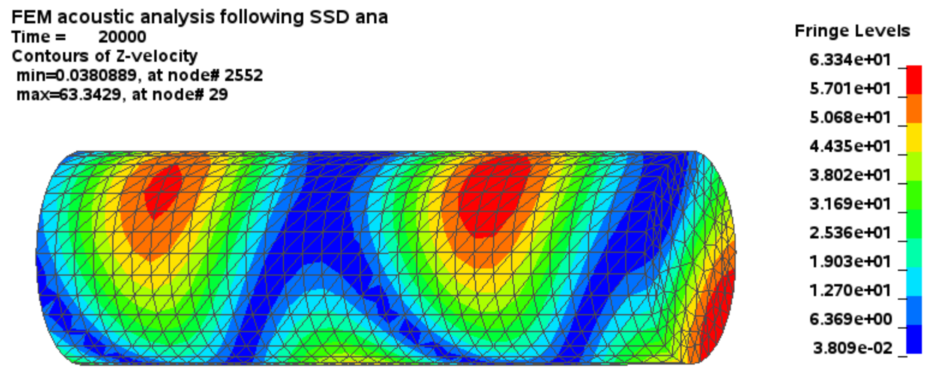
f =5000 Hz



f =10000 Hz



f =15000 Hz



f =20000 Hz

5.

NVH APPLICATION

Coupling acoustics with SSD

FREQUENCY_DOMAIN_SSD

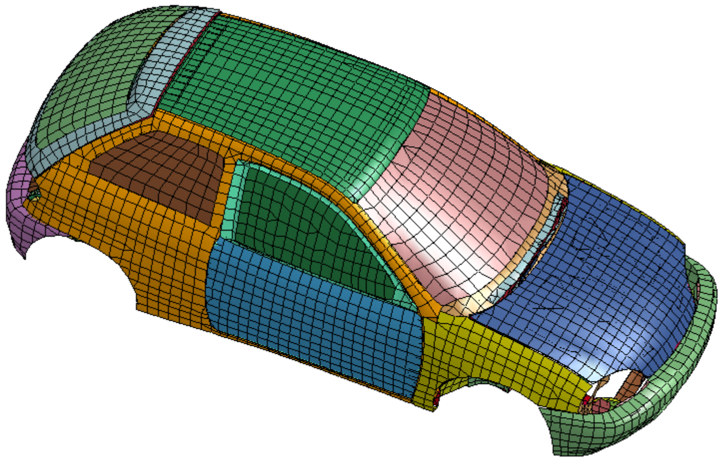
⇩

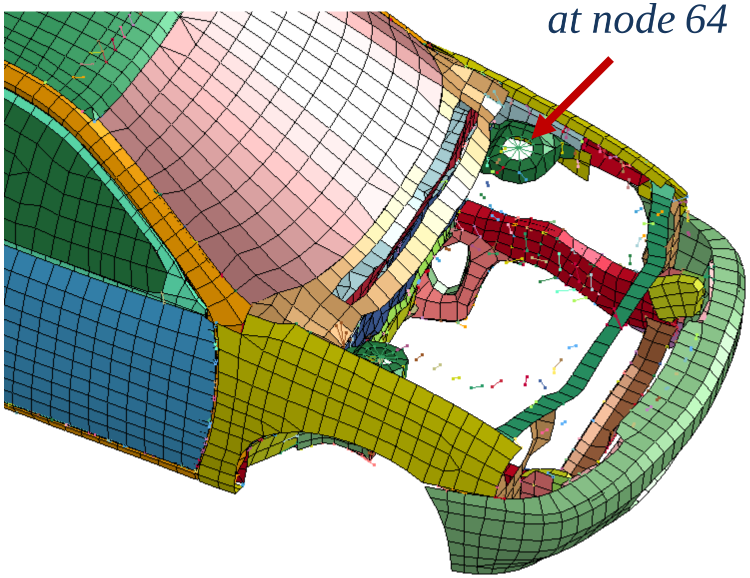
FREQUENCY_DOMAIN_ACOUSTIC_BEM

Step 1: User uses the steady state dynamics feature to compute the vibration response of the structure, due to harmonic loading;

Step 2: The boundary velocity or acceleration obtained in step 1 is used as input for BEM acoustic computation.

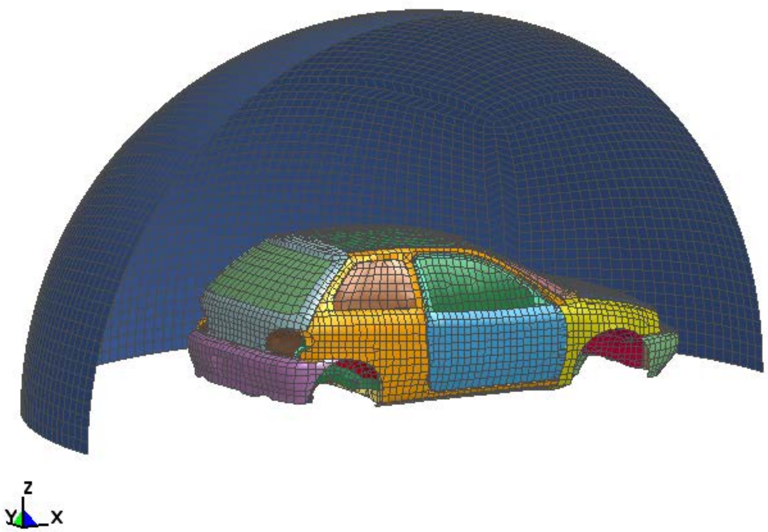
Example: radiated noise by a car



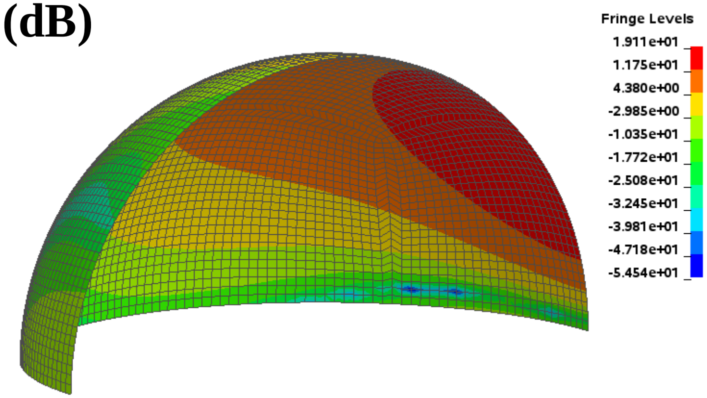


- The trimmed model has 15906 nodes and 13216 elements. Total no. of parts = 96.
- Additional components are represented by lumped mass.
- Harmonic unit force excitation is given in frequency range 1-101 Hz, at node 64 (attachment point).
- Modes with eigen frequencies 1-120 Hz are employed in SSD.
- Radiated noise is given on surrounding sphere, or rectangular plate for visualization.

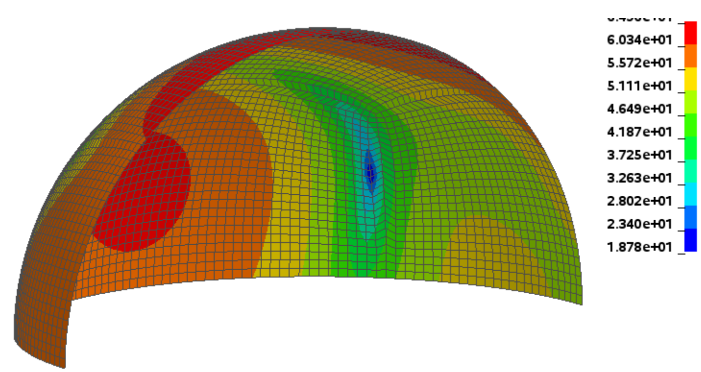
Sound Pressure Level distribution (dB)



- The radius of the sphere is 3 m

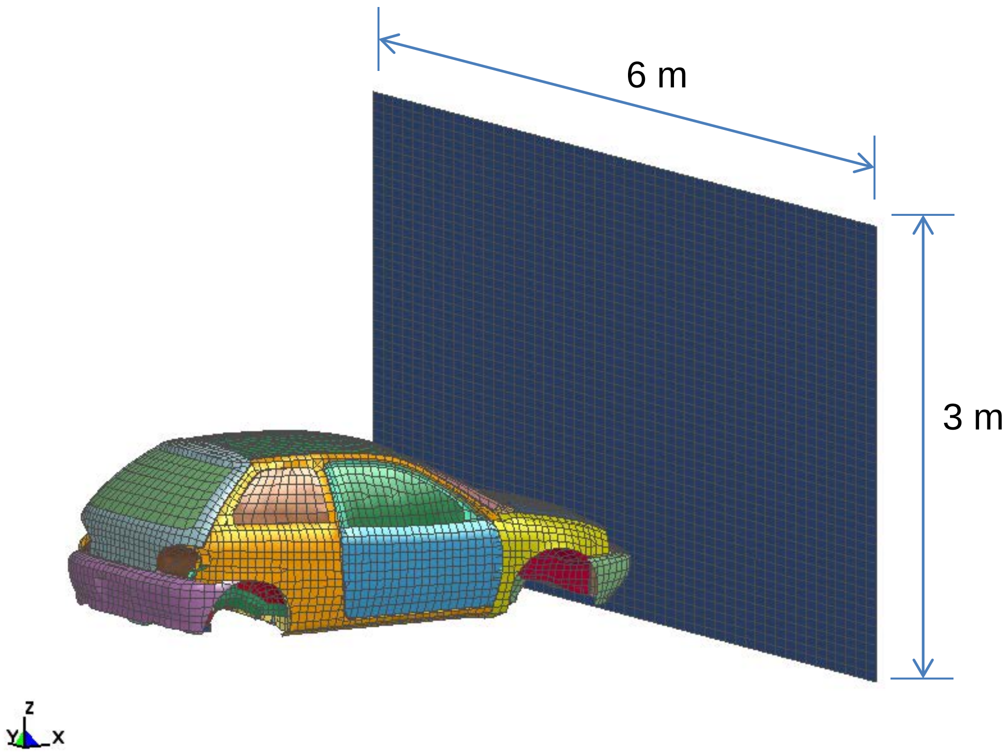


freq = 11 Hz

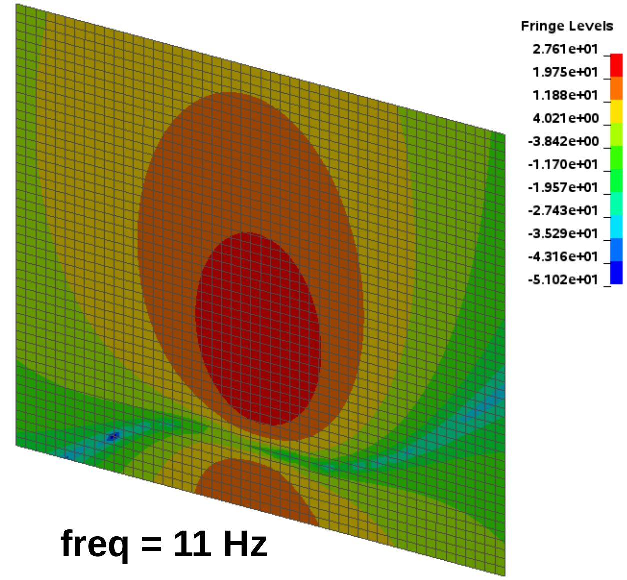


freq = 101 Hz

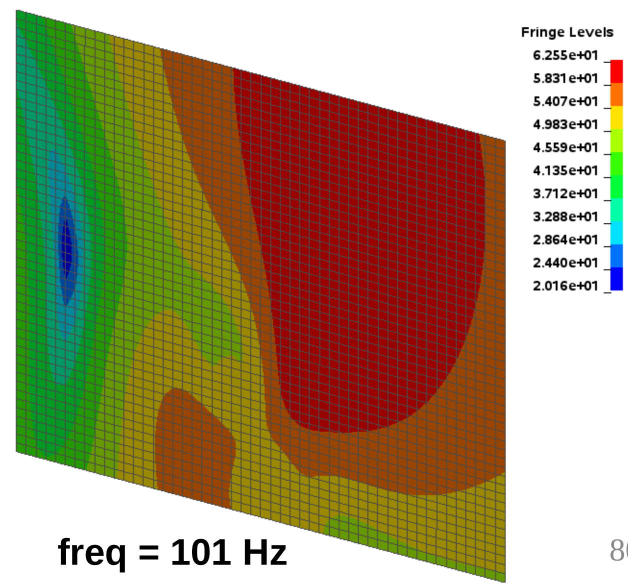
Sound Pressure Level distribution (dB)



- The plate is 0.2 m away from the vehicle



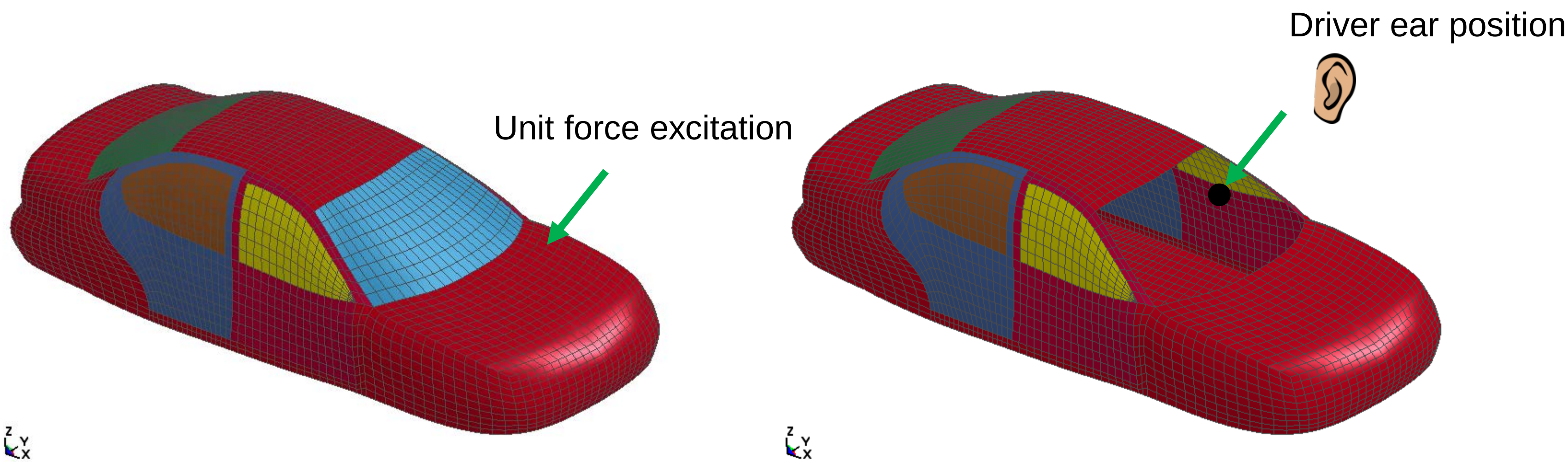
freq = 11 Hz



freq = 101 Hz

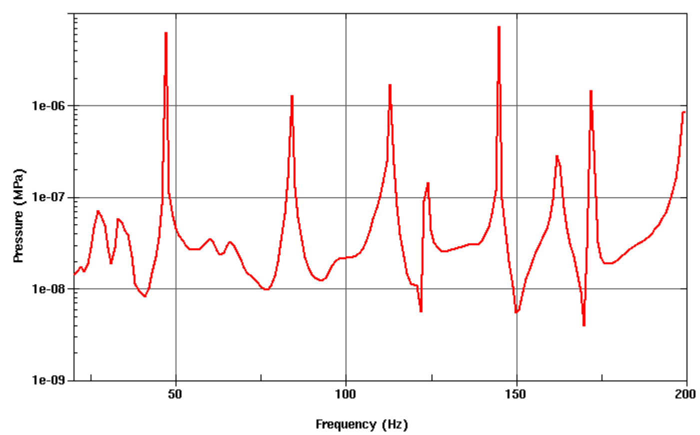
Example: Auto Acoustic FRF

A simplified auto body model without any interior details



Analysis steps:

1. Modal analysis
2. Steady state dynamics
3. Boundary element acoustics



All done in one run

6

FUTURE DEVELOPMENTS

- SEA for high frequency acoustics
- Modal acoustic transfer vector
- Fast multi-pole BEM for acoustics
- Infinite elements in acoustic FEM
- Strong coupling of frequency domain BEM with structures
- Acoustic modal analysis
- Rolling tire noise
- Suggestions from users …

Thank you!