New frequency domain features in LS-DYNA®

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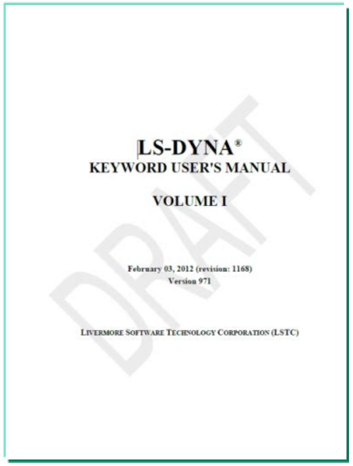
Outline

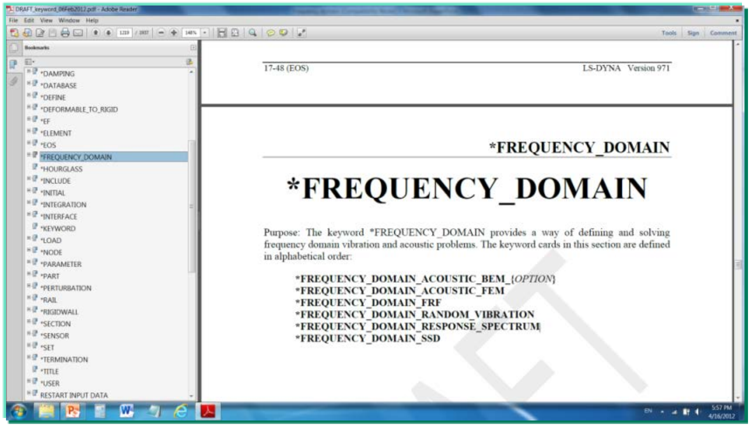
- Introduction
- Frequency response functions
- Steady state dynamics
- Random vibration & fatigue
- Response spectrum analysis
- Acoustic analysis by BEM/FEM
- Conclusion & future work

1. introduction

Keywords for frequency domain analysis

- FREQUENCY_DOMAIN_FRF
- FREQUENCY_DOMAIN_SSD
- FREQUENCY_DOMAIN_RANDOM_VIBRATION_{OPTION}
- FREQUENCY_DOMAIN_ACOUSTIC_BEM_{OPTION}
- FREQUENCY_DOMAIN_ACOUSTIC_FEM
- FREQUENCY_DOMAIN_RESPONSE_SPECTRUM





Frequency domain vs. time domain

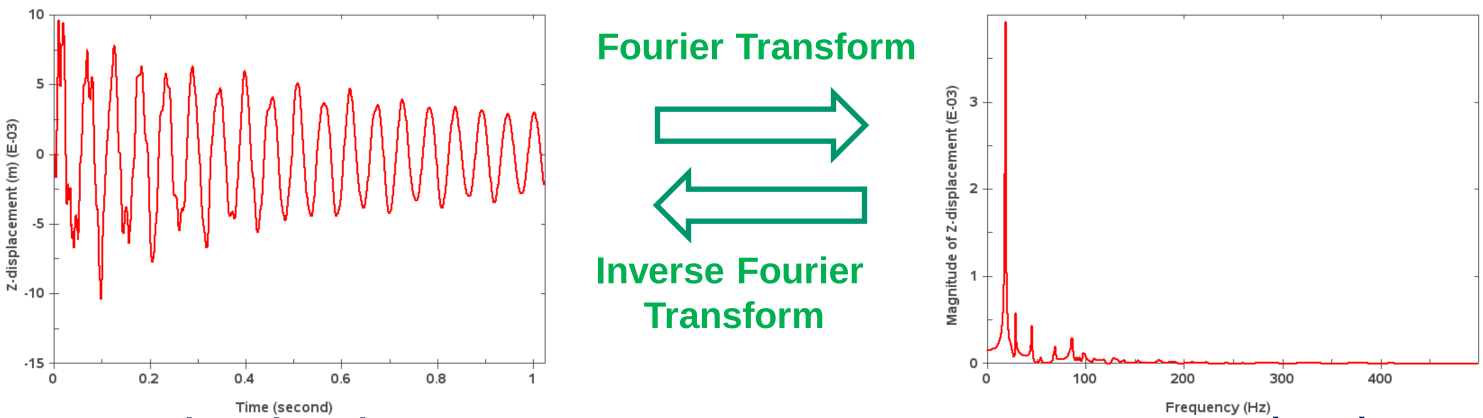
- A time-domain graph shows how a signal changes over time
- A frequency-domain graph shows the distribution of the energy (magnitude, etc.) of a signal over a range of frequencies

Frequency domain analysis

- ✓ Harmonic, periodic loading
- ✓ Resonance
- ✓ Linear dynamics
- ✓ Long history (fatigue testing)
- ✓ Non-deterministic load (random analysis)

Time domain analysis

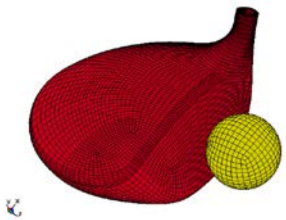
- ✓ Transient analysis (penetration)
- ✓ Impact (crash simulation)
- ✓ Large deformation
- ✓ Non-linearity (fracture, contact)

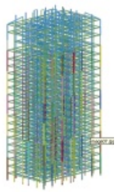


Time domain **Frequency domain**

Application of frequency domain features

- ✓ Vehicle NVH
  - *Interior noise*
  - *Exterior radiated noise*
  - *Vibration*
- ✓ Vehicle Durability
  - *Cumulative damage ratio*
  - *Expected life (mileage)*
- ✓ Aircraft / rocket / spacecraft vibro-acoustics
- ✓ Durability analysis of machines and electronic devices
- ✓ Acoustic design of sports products
- ✓ Civil Engineering
  - *Architectural acoustics (auditorium, concert hall)*
  - *Earthquake resistance*
- ✓ Off-shore platforms, wind turbine, etc.
  - *Random vibration*
  - *Random fatigue*





New databases in frequency domain

- BINARY databases

  Keyword ***DATABASE_FREQUENCY_BINARY_*{OPTION}****

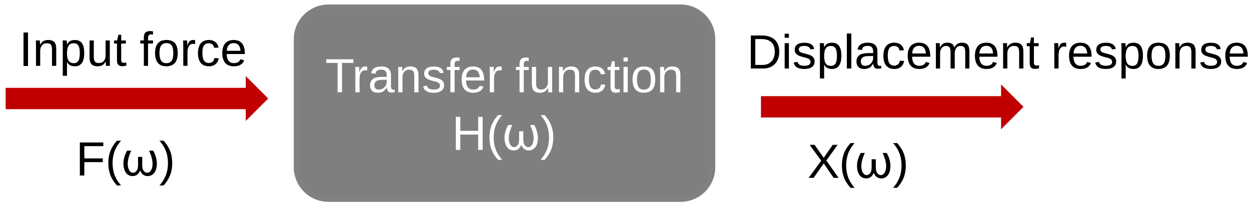
Database	lspcode	used for
D3SSD	21	Steady state dynamics
D3SPCM	22	Response spectrum analysis
D3PSD	23	Random vibration PSD
D3RMS	24	Random vibration RMS
D3FTG	25	Random vibration fatigue
D3ACS	26	FEM acoustics
D3ATV	27	BEM acoustic transfer vector

- ASCII databases
  - ✓ FRF: frf_amplitude, frf_angle, frf_real, frf_imag
  - ✓ BEM acoustics: Press_Pa, Press_dB, bepres, fringe_*, panel_contribution_NID,
  - ✓ SSD: elout_ssd, nodout_ssd, …

Accessible to LS-PREPOST !

2. Frequency response function

Introduction: frf



$$X(\omega) = H(\omega) \cdot F(\omega) \qquad H(\omega) = \frac{X(\omega)}{F(\omega)}$$

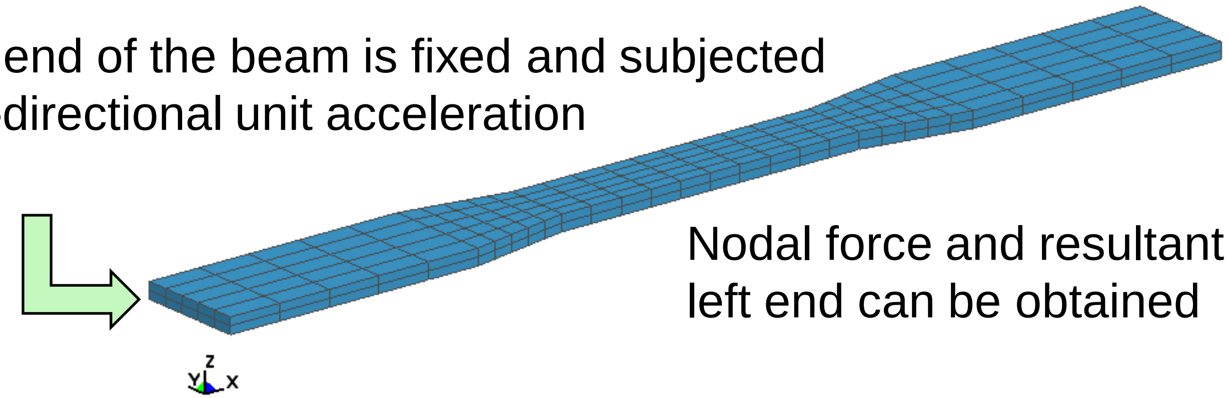
- Foundation of modern experimental system analysis and experimental modal analysis
- Expresses structural response due to unit load as a function of frequency
- property of structure system
- complex function, with real / imaginary components, or magnitude / phase angle pairs
- Efficient restart based on modal analysis results
- Important application in transfer path analysis

FRF formulations

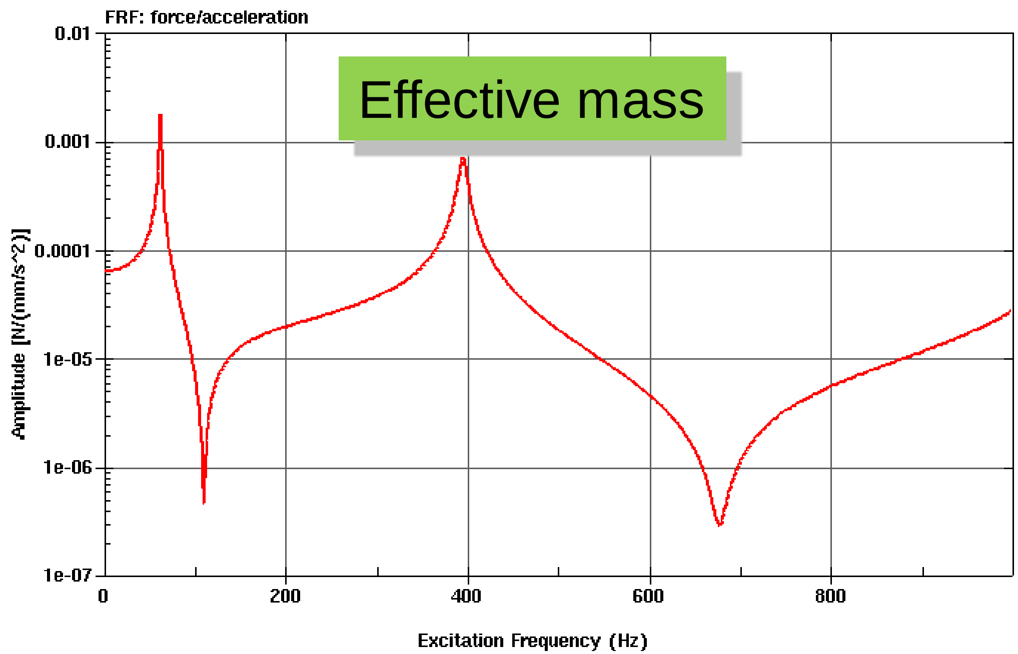
Accelerance, Inertance	$\frac{\text{Acceleration}}{\text{Force}}$
Effective Mass	$\frac{\text{Force}}{\text{Acceleration}}$
Mobility	$\frac{\text{Velocity}}{\text{Force}}$
Impedance	$\frac{\text{Force}}{\text{Velocity}}$
Dynamic Compliance, Admittance, Receptance	$\frac{\text{Displacement}}{\text{Force}}$
Dynamic Stiffness	$\frac{\text{Force}}{\text{Displacement}}$

Nodal force/resultant force for a beam model

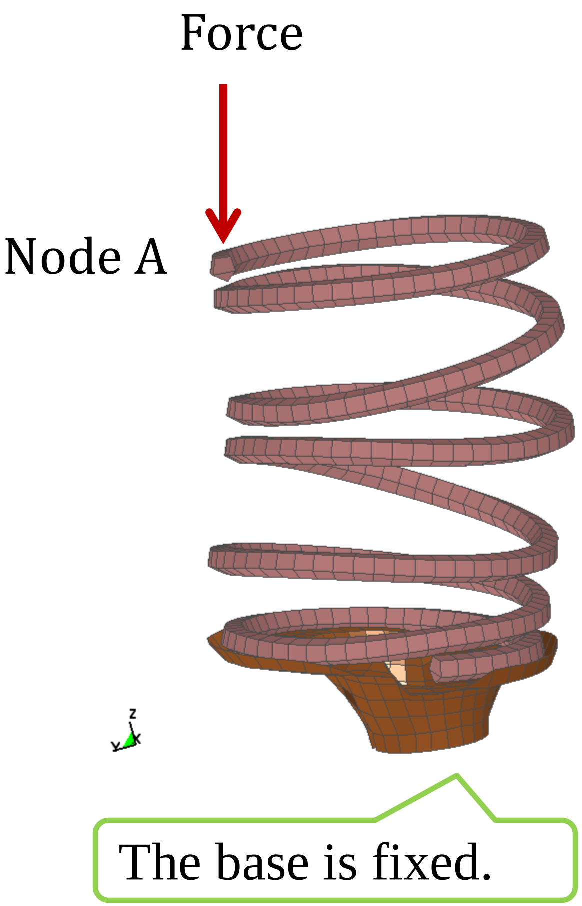
Left end of the beam is fixed and subjected to z-directional unit acceleration



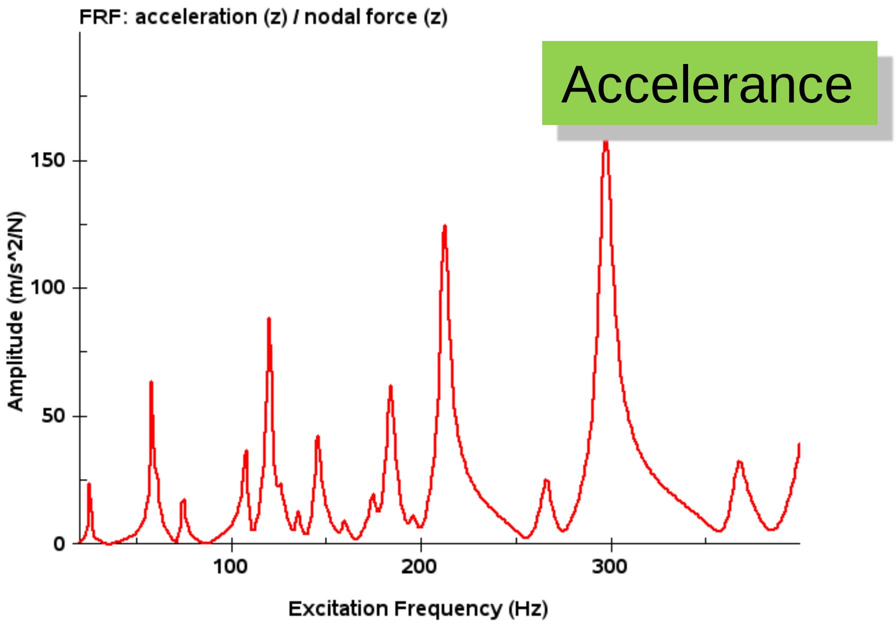
Nodal force and resultant force FRF at the left end can be obtained



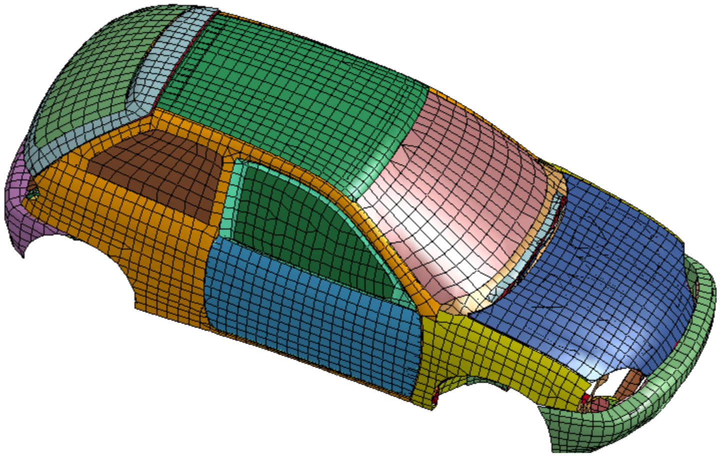
FRF for a spring in suspension system



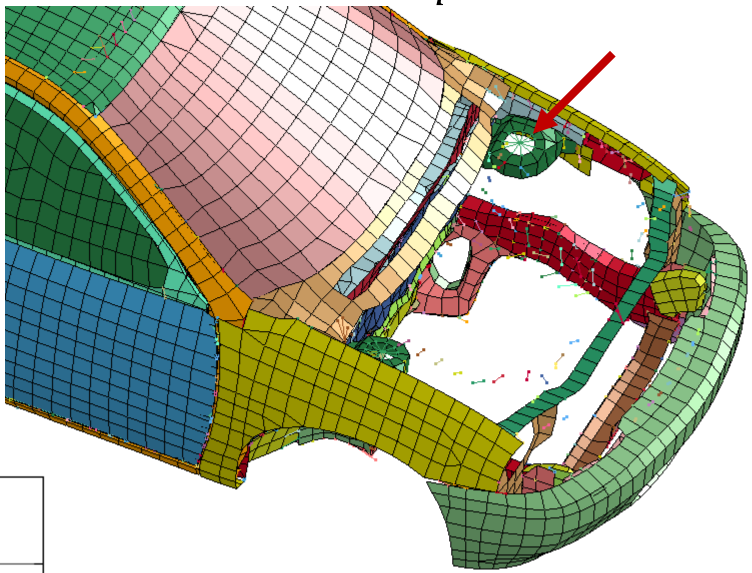
Point FRF at node A is computed
FRF = acceleration / nodal force

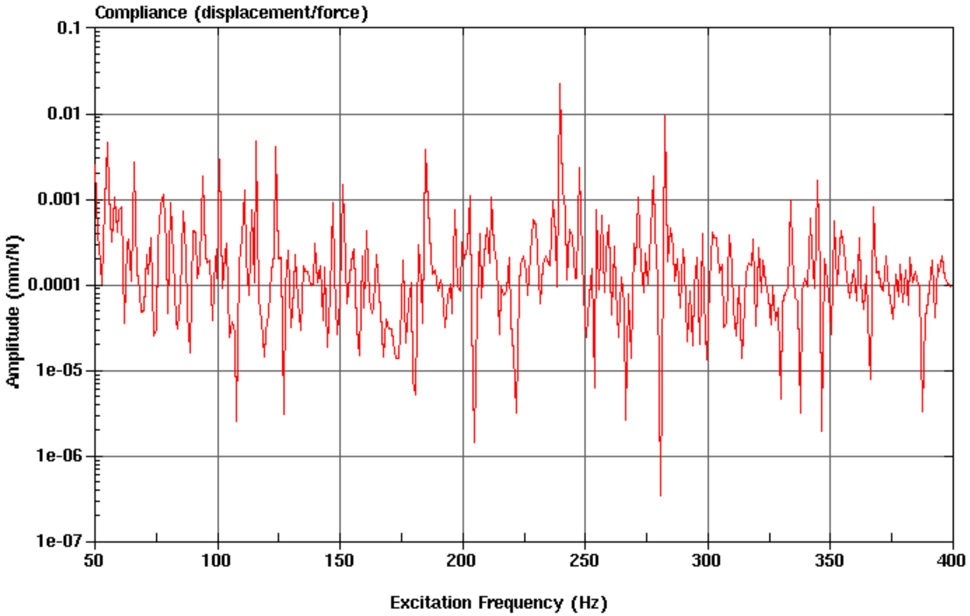


FRF for a simplified car body



Nodal force applied and displacement measured



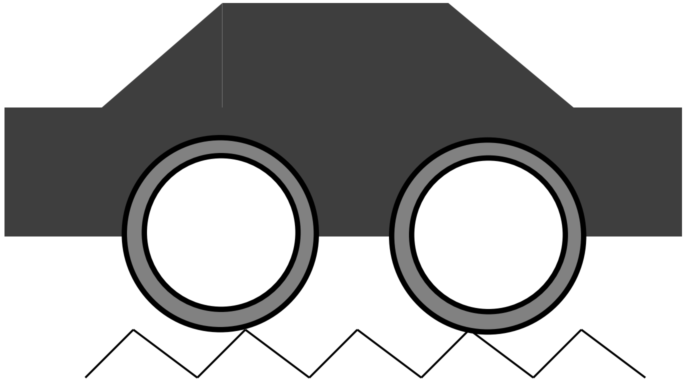


Dynamic compliance

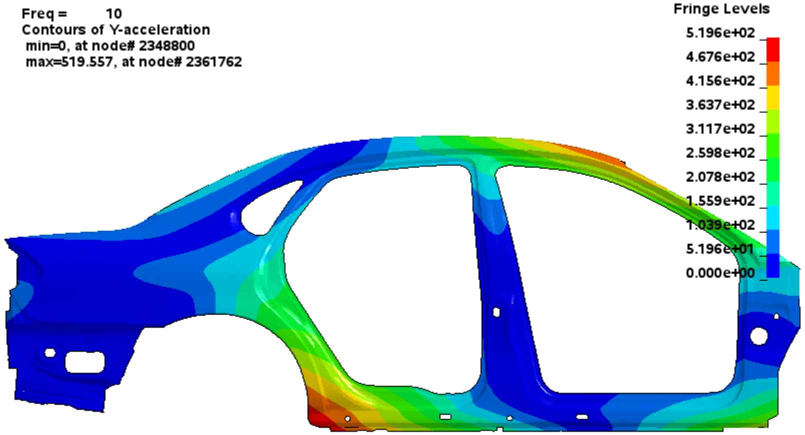
3. Steady state dynamics

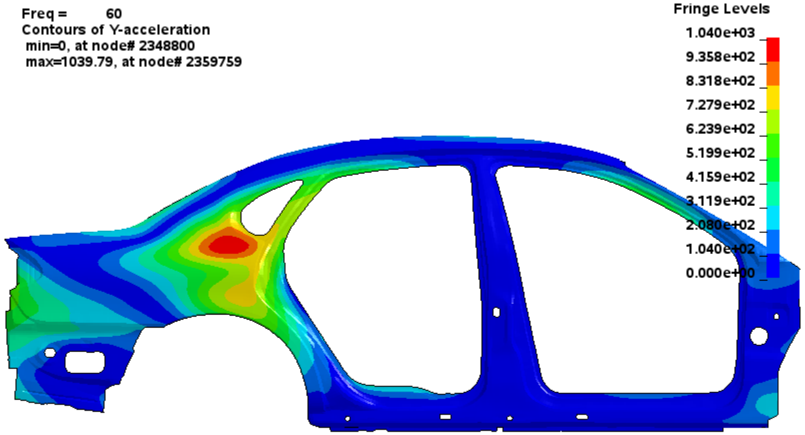
Introduction: SSD

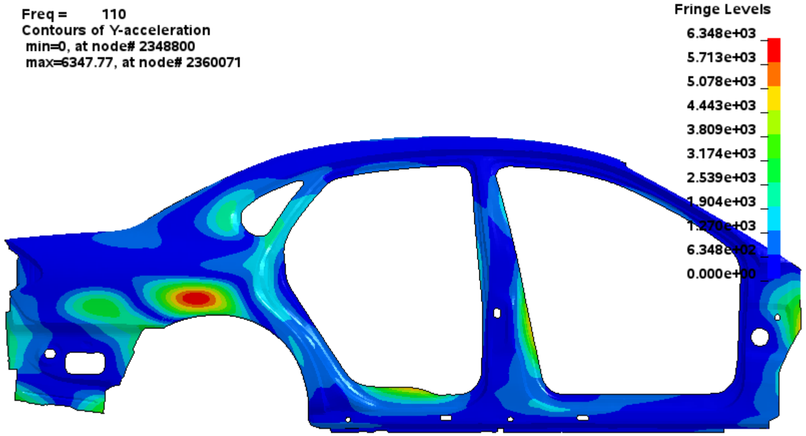
- *Harmonic excitation* is often encountered in engineering systems. It is commonly produced by the unbalance in rotating machinery.
- The load may also come from periodical load, e.g. in fatigue test.
- The excitation may also come from uneven base, e.g. the force on tires running on a zig-zag road.
- Both input and output are given as complex variables (e.g. amplitude / phase angle pairs)
- Based on modal approach (modal analysis is performed first)
- May be called as
  - Harmonic vibration
  - Steady state vibration
  - Steady state dynamics

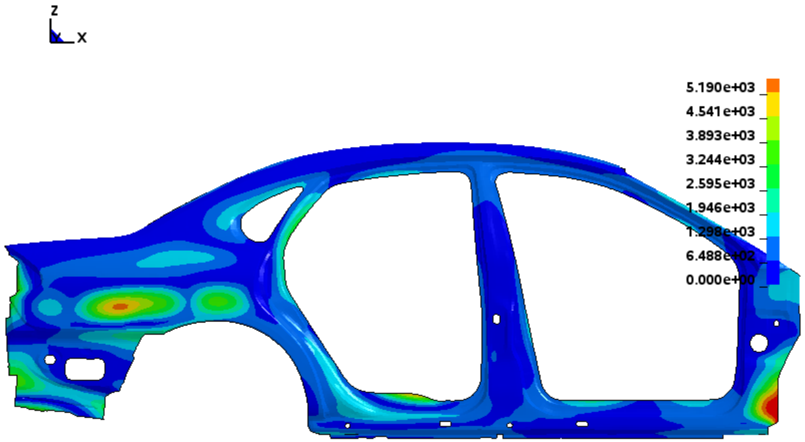


Acceleration SSD for body frame









(given by d3ssd)

4. Random vibration & fatigue

Introduction: random vibration

Why we need random vibration analysis?

o In many cases, the loading on a structure is undeterministic

o Many vibration environments are not related to a specific driving frequency (may have input from multiple sources)

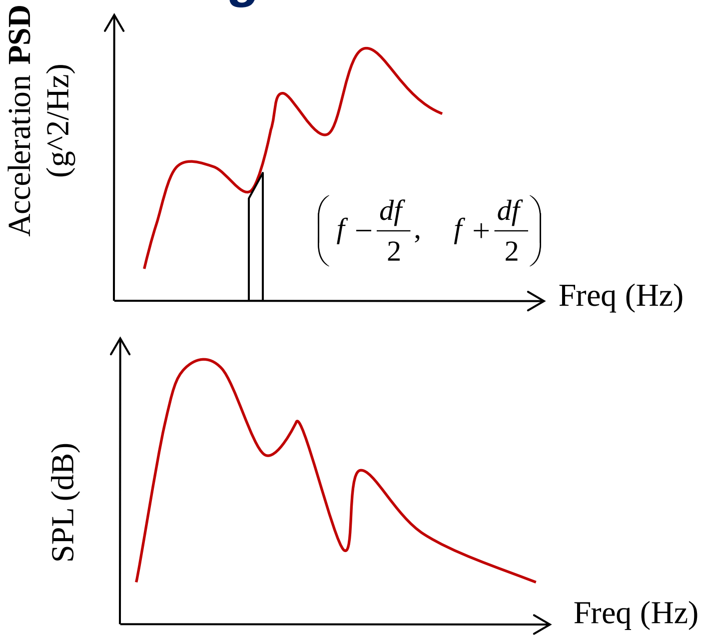
o Provide input data for random fatigue and durability analysis

Examples

- Fatigue
- Wind-turbine
- Air flow over a wing or past a car body
- Acoustic input from jet engine exhaust
- Earthquake ground motion
- Wheels running over a rough road
- Ocean wave loads on offshore platforms

Based on Boeing's N-FEARA package

Loading: PSD or SPL

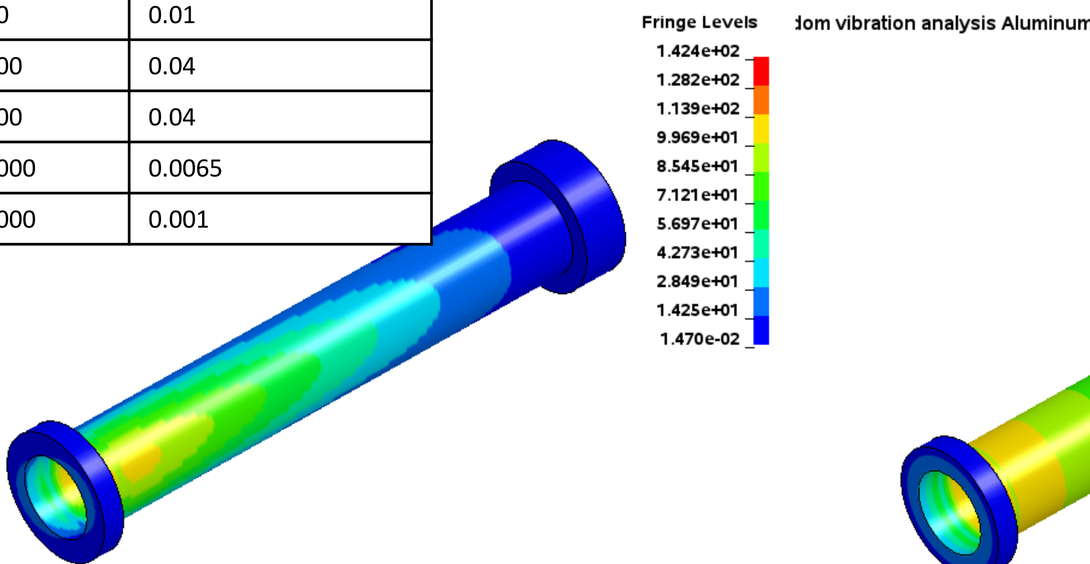


A pipe under base acceleration

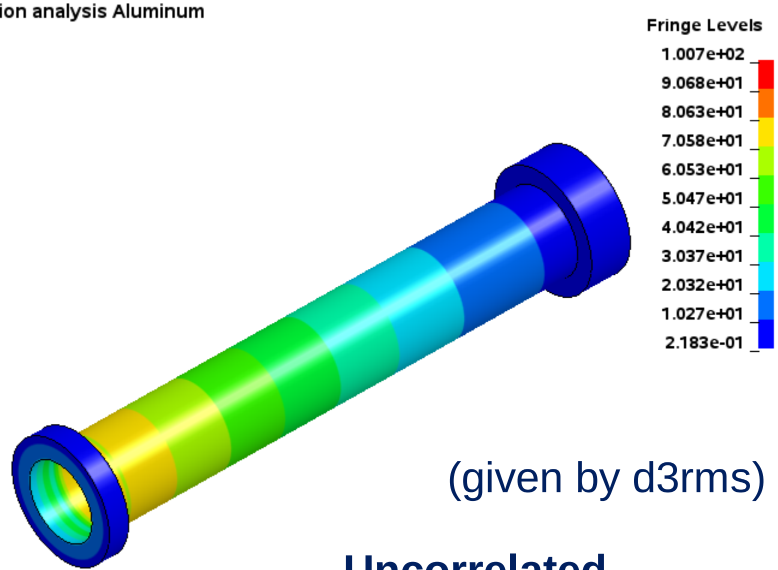
The model is a simple pipe with 83700 elements and 105480 nodes. It is subjected to base acceleration PSD 1) in x, y and z-directions correlated; 2) in x, y and z-directions uncorrelated.

F (Hz)	Acce. Psd (g^2/Hz)
5	0.01
40	0.01
100	0.04
500	0.04
1000	0.0065
2000	0.001

RMS of Von Mises stress



Correlated



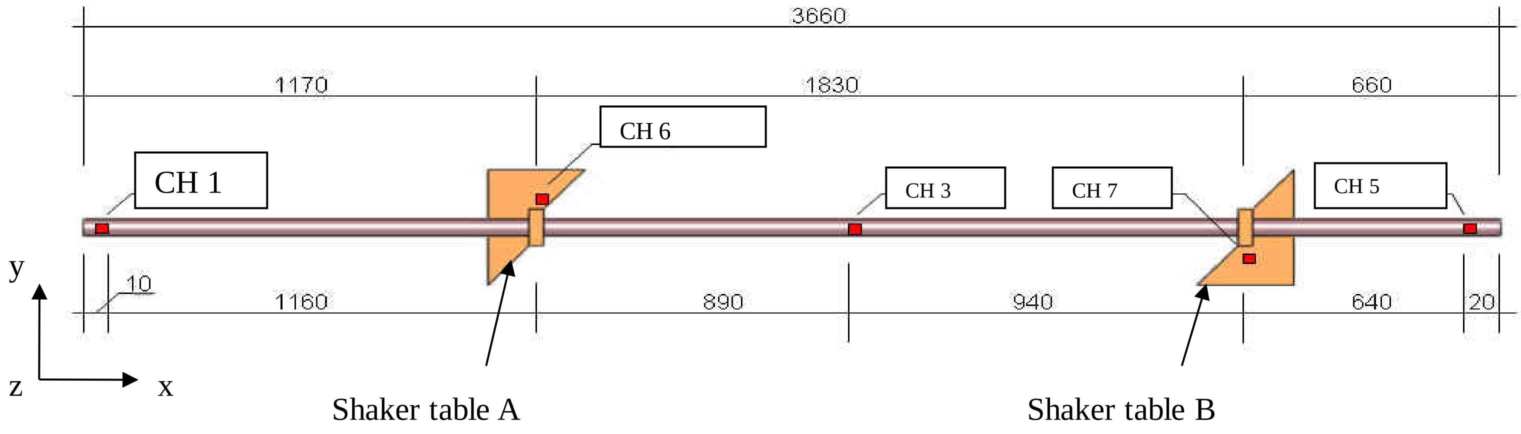
(given by d3rms)

Uncorrelated

Max Von Mises RMS stress (MPa)

Correlated	Uncorrelated
142.4	100.7

Shaker table test



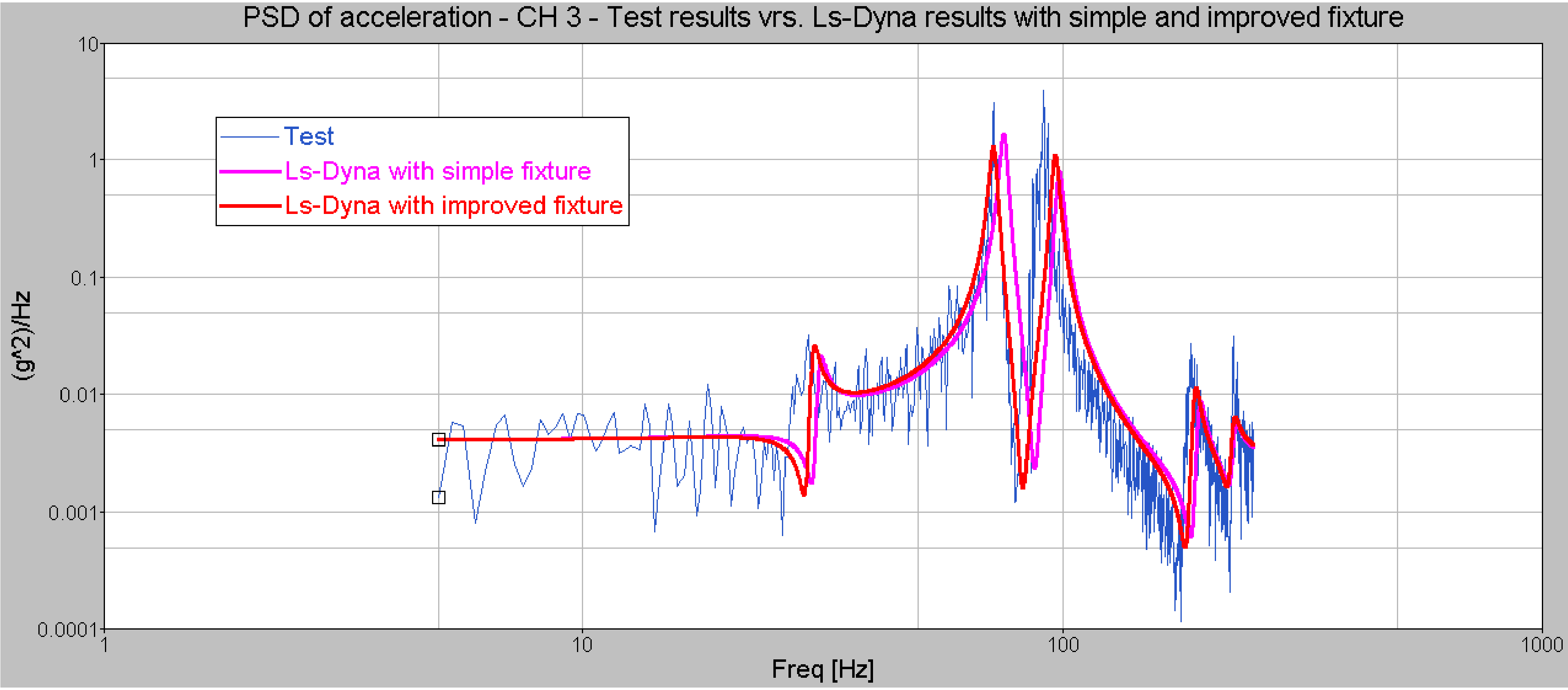
Tube thickness = 3.3 mm

The tube was fixed to the shaker tables using aluminum blocks which surrounded the tube and were tightened using screws.

Base acceleration PSD load

Total : 1.00 [Grms]

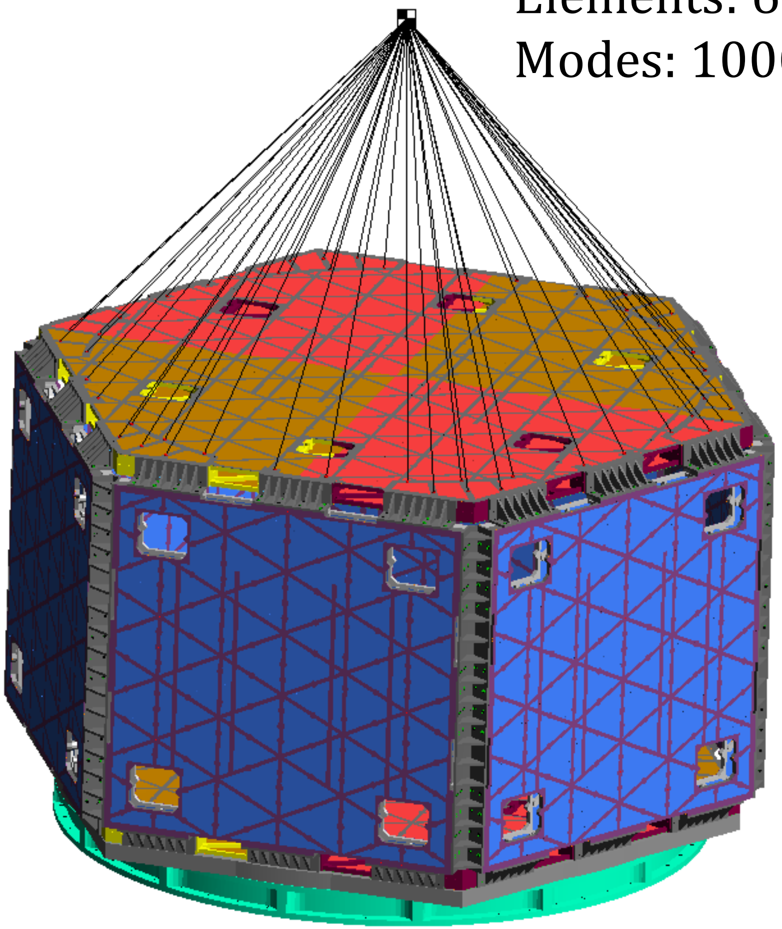
No.	Freq.	g^2/Hz
1	5	0.004082
2	250	0.004082

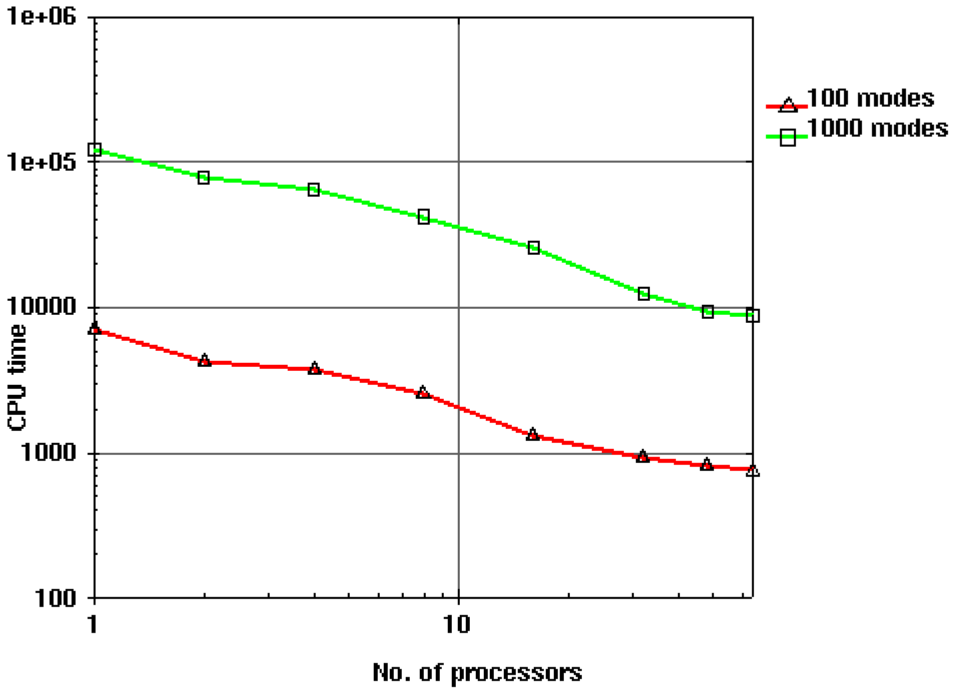


Ofir Shor, Yoav Lev, Yun Huang, *Simulation of a Thin Walled Aluminum Tube Subjected to Base Acceleration Using LS-DYNA's Vibro-Acoustic Solver*, 11th International LS-DYNA Users' Conference, Dearborn, MI, 2010.

MPP random vibration analysis

Nodes: 800k
Elements: 660k
Modes: 1000





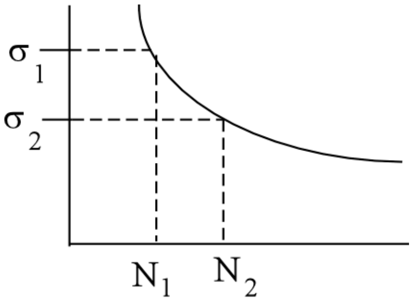
Introduction: random vibration fatigue

FREQUENCY_DOMAIN_RANDOM_VIBRATION_*FATIGUE

- Calculate fatigue life of structures under random vibration
- Based on S-N fatigue curve
- Based on probability distribution & Miner's Rule of Cumulative Damage Ratio

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

- Schemes:
  - ✓ *Steinberg's Three-band technique*
  - ✓ *Dirlik method*
  - ✓ *Narrow band method*
  - ✓ *Wirsching method*
  - ✓ *…*



Typical SN (or Wöhler) curve

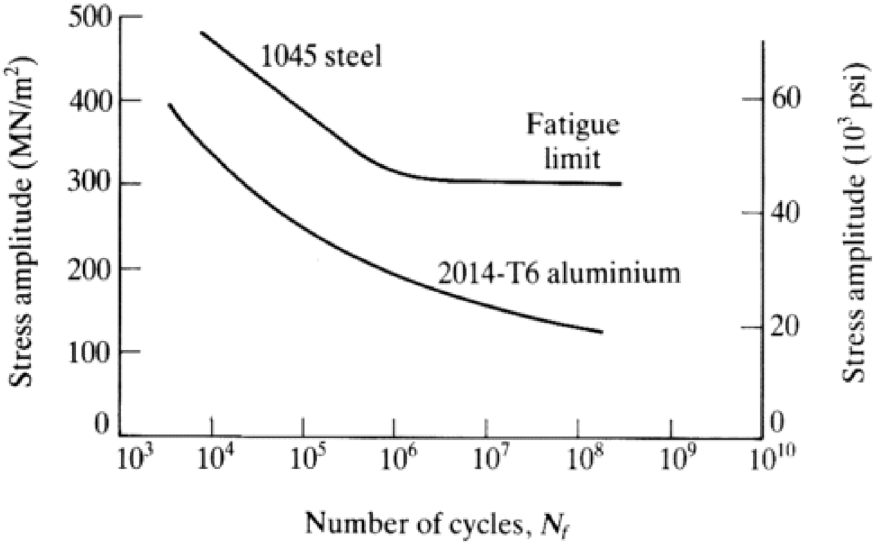
S-N fatigue curve definition

- By *define_curve
- By equation

$$N \cdot S^m = a$$

$$\log(S) = a - b \cdot \log(N)$$

N: number of cycles for fatigue failure
S: stress

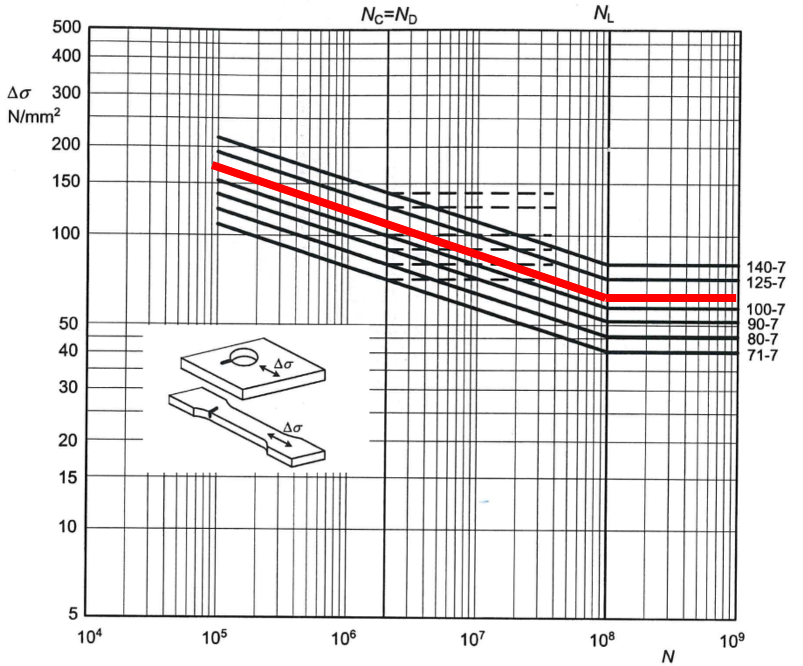


Source of picture: http://www.efunda.com

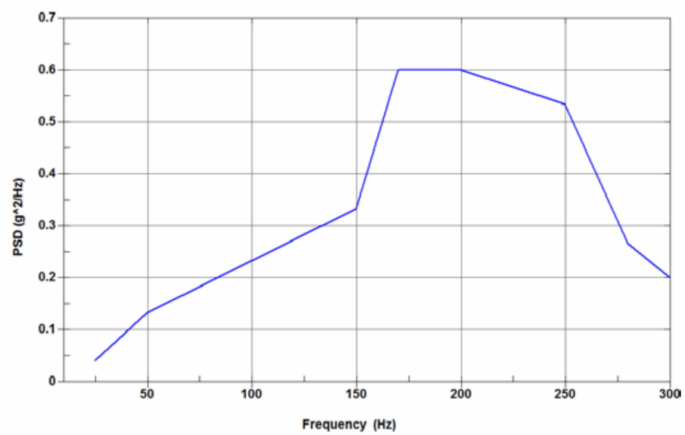
A beam with pre-defined notch

Aluminum alloy 5754
ρ = 2700 Kg/m[3]
E = 70,000 MPa
ν = 0.33

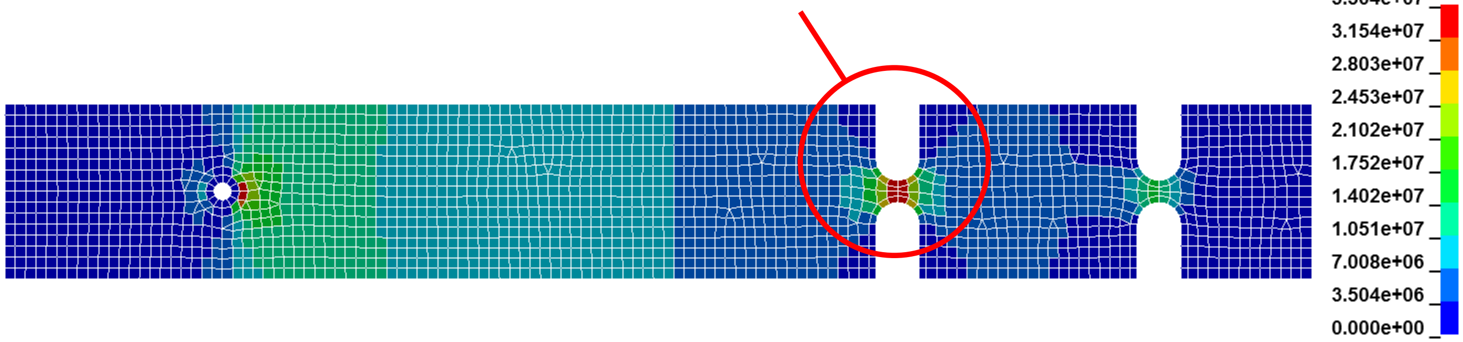
Base acceleration is applied at the edge of the hole



Acceleration PSD
(exposure time: 1800 seconds)



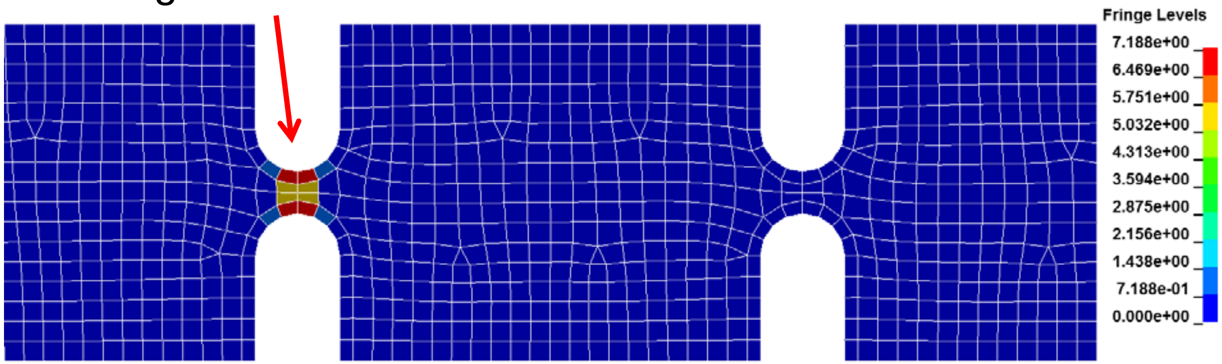
RMS S_{xx} = 35.0 MPa at critical point



Analysis method	Expected life	Damage ratio
Experiment	7mn 25s	-
Steinberg	4mn 10s	7.19
Dirlik	5mn 25s	5.54
Narrow Band	2mn 05s	14.41
Wirsching	5mn 45s	5.08
Chaudhury & Dover	6mn 03s	6.03
Tunna	4mn 06s	7.31
Hancock	22mn 18s	1.35

CODE	RMS Sxx
ANSYS	33.5 MPa
RADIOSS® BULK	35.7 MPa
LS-DYNA	35.0 MPa

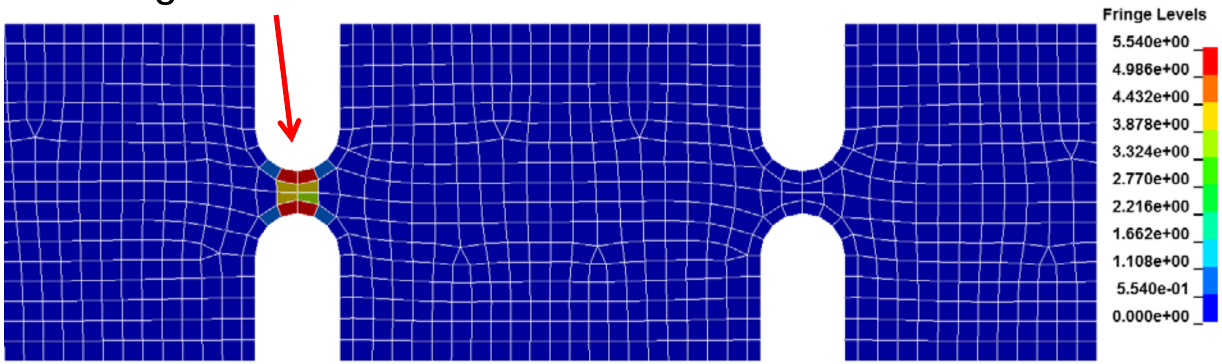
Damage ratio = 7.188



Cumulative damage ratio by Steinberg's method

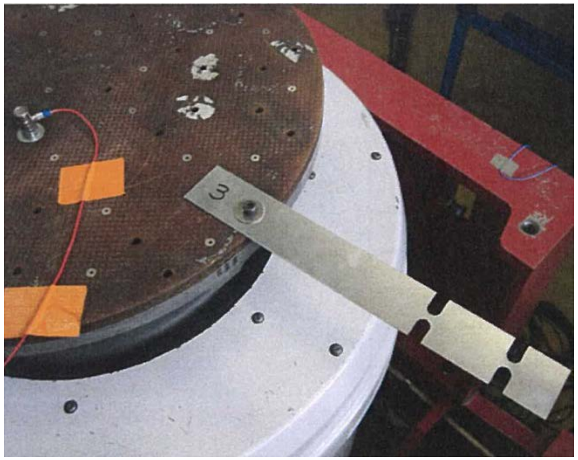
(given by d3ftg)

Damage ratio = 5.540

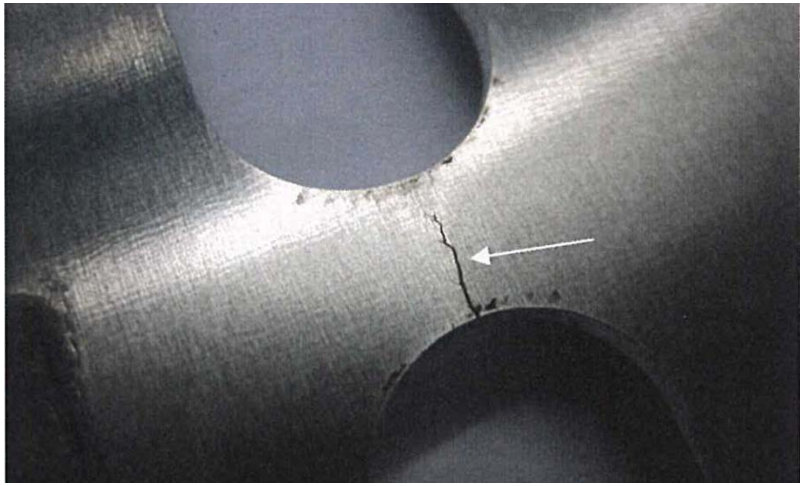


Cumulative damage ratio by Dirlik method

Experiment setup



Failure at the notched point in experiment



How to include pre-existing fatigue damage

*FREQUENCY_DOMAIN_RANDOM_VIBRATION_*FATIGUE**

Card1	1	2	3	4	5	6	7	8
Variable	MDMIN	MDMAX	FNMIM	FNMAX	RESTRT	MFTG	RESTRM	**INFTG**
Type	I	I	F	F	I	I	I	I
Default	1		0.0		0	0	0	0

Define Card 7 if option FATIGUE is used and INFTG=1.

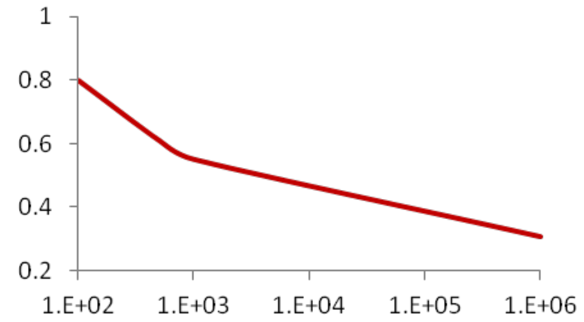
Card7	1	2	3	4	5	6	7	8
Variable	**FILENAME**							
Type	C							
Default	d3ftg							

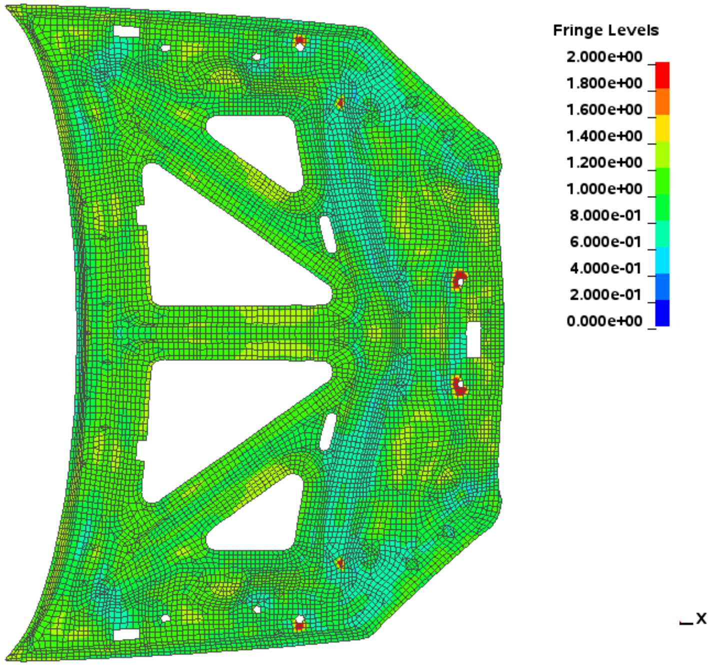
VARIABLE	DESCRIPTION
INFTG	Flag for including initial damage ratio. EQ.0: no initial damage ratio, EQ.1: read existing d3ftg file to get initial damage ratio.
FILENAME	Path and name of existing binary database (by default, D3FTG) for initial damage ratio.

Regarding fatigue life for stress below last pt on SN curve

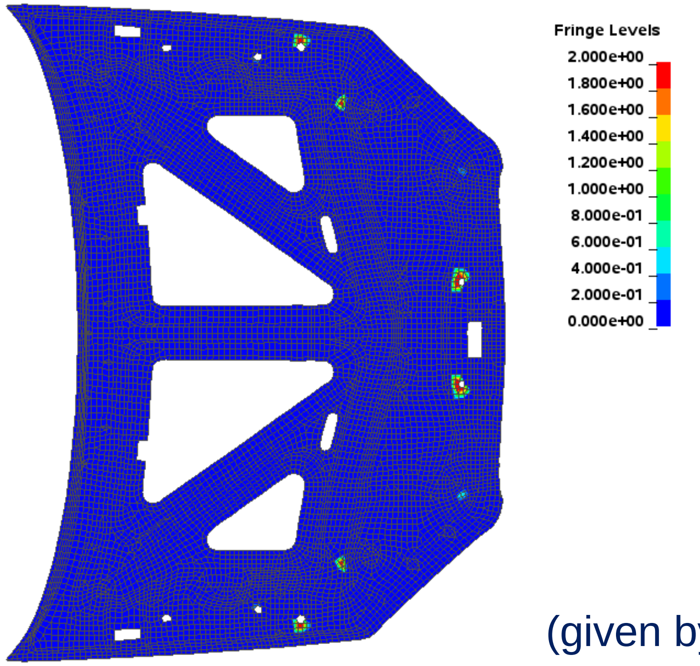
SNLIMT

Fatigue life for stress lower than the lowest stress on S-N curve.
EQ.0: use the life at the last point on S-N curve
EQ.1: extrapolation from the last two points on S-N curve
EQ.2: infinity.





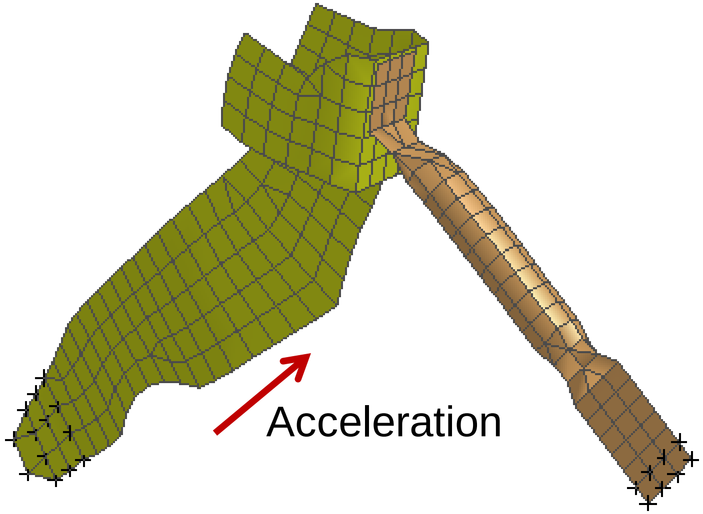
SNLIMT = 0

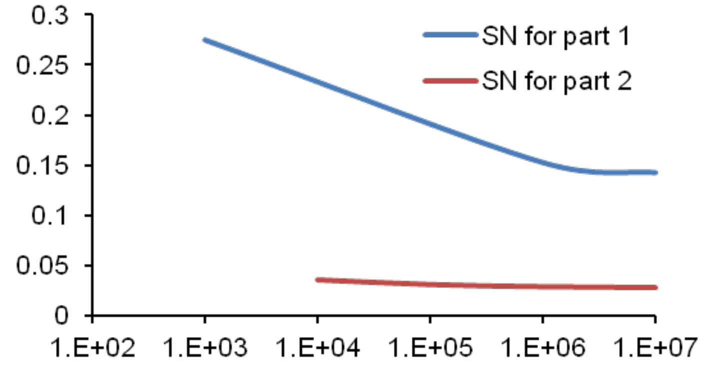


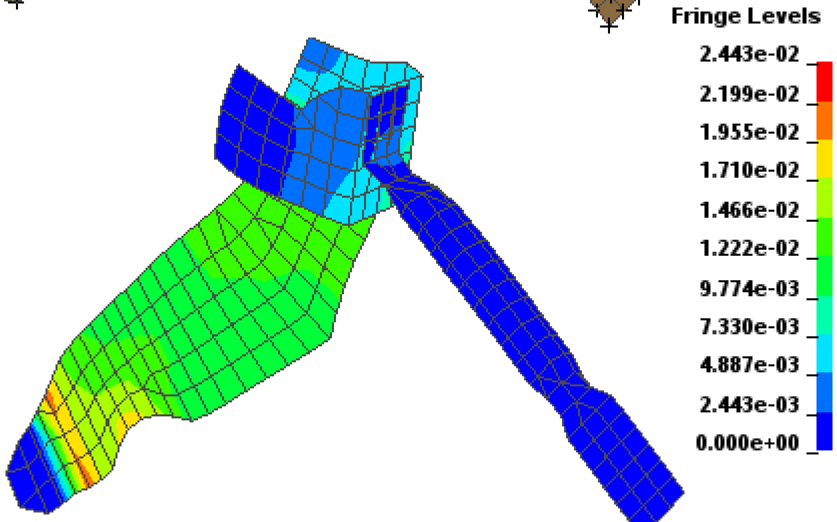
(given by d3ftg)

SNLIMT = 2

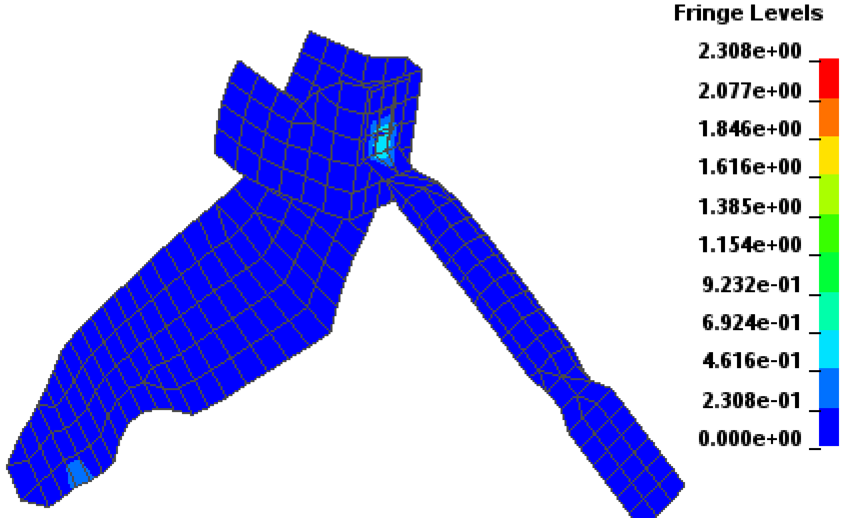
Example: multi S-N curves in one model







RMS of Von Mises stress (d3rms)



Accumulative damage ratio (d3ftg)

5. Response spectrum analysis

Introduction: response spectrum analysis

***FREQUENCY_DOMAIN_RESPONSE_SPECTRUM**

- Use various mode combination methods to evaluate peak response of structure due to input spectrum.
- The input spectrum is the peak response (acceleration, velocity or displacement) of single degree freedom system with different natural frequencies.
- The input spectrum is dependent on damping (using ***DEFINE_TABLE** to define the series of excitation spectrum corresponding to each damping ratio).
- Output binary database: d3spcm (accessible by LS-PREPOST).
- It is an approximate method.
- It has important application in *earthquake engineering, nuclear power plants design* etc.

Capabilities

Mode combination

- o SRSS method
- o NRC Grouping method
- o CQC method
- o Double Sum methods
  - ✓ Rosenblueth-Elorduy coefficient
  - ✓ Gupta-Cordero coefficient
  - ✓ Modified Gupta-Cordero coefficient
- o NRL SUM method
- o Rosenblueth method

Input spectrum

- o Base velocity
- o Base acceleration
- o Base displacement
- o Nodal force
- o Pressure

Frequency interpolation

- o Logarithmic
- o Semi-logarithmic
- o Linear

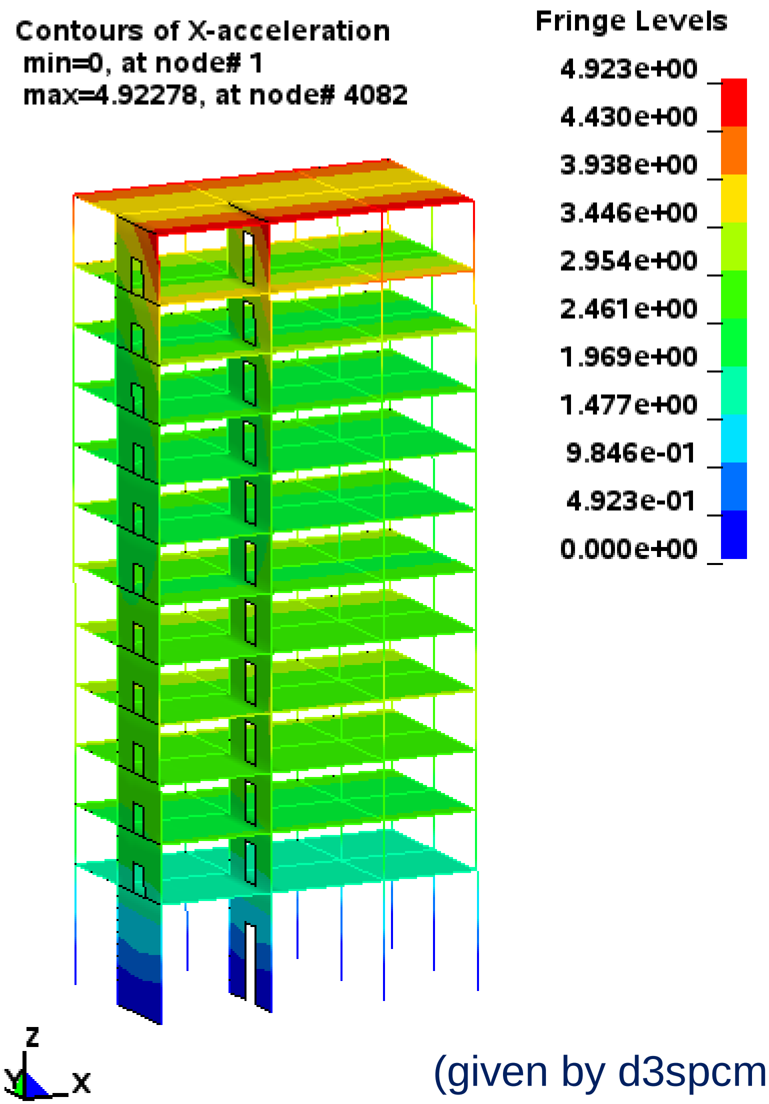
Results

- o BINARY plot file: d3spcm
- o ASCII files: nodout_spcm, elout_spcm

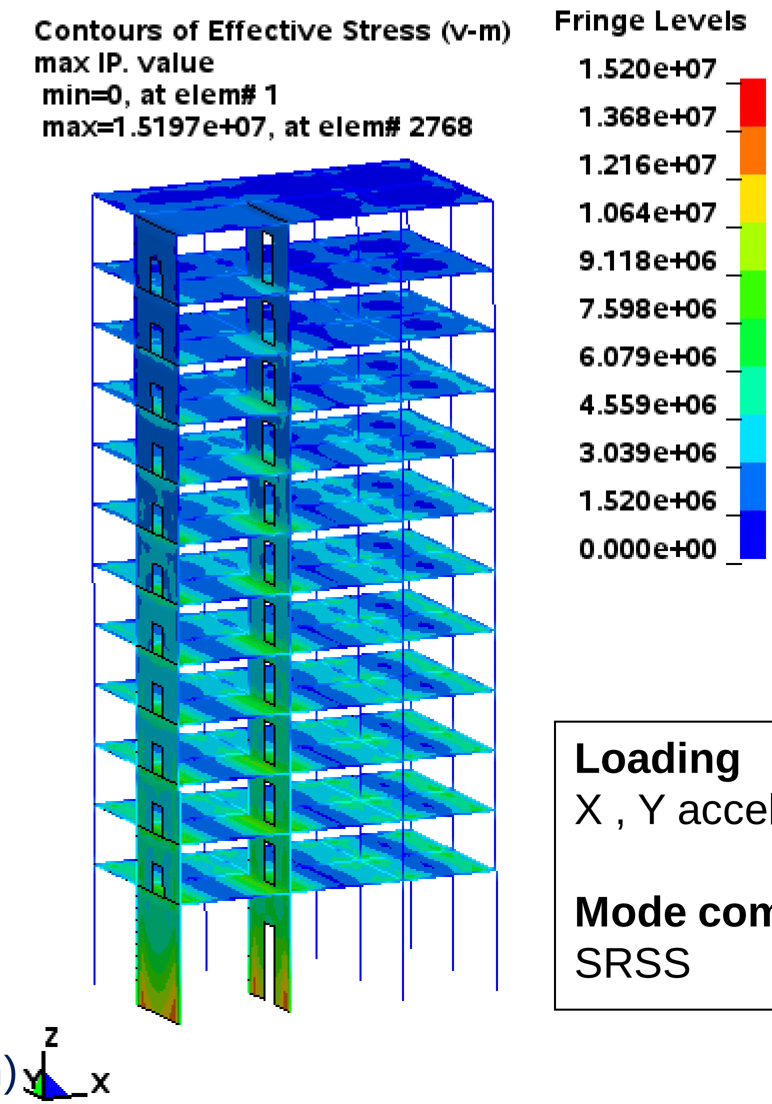
Applications

- o Civil and hydraulic buildings
  - ✓ Dams
  - ✓ Bridges
  - ✓ High buildings
- o Nuclear power plants

Example: multi-story tower



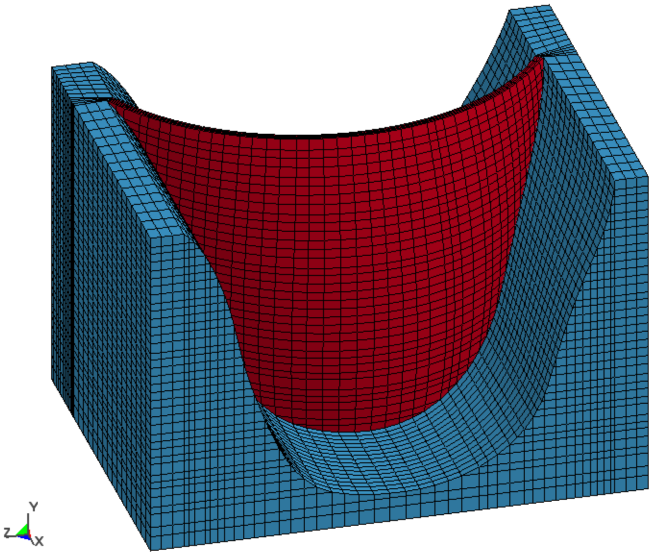
(given by d3spcm)



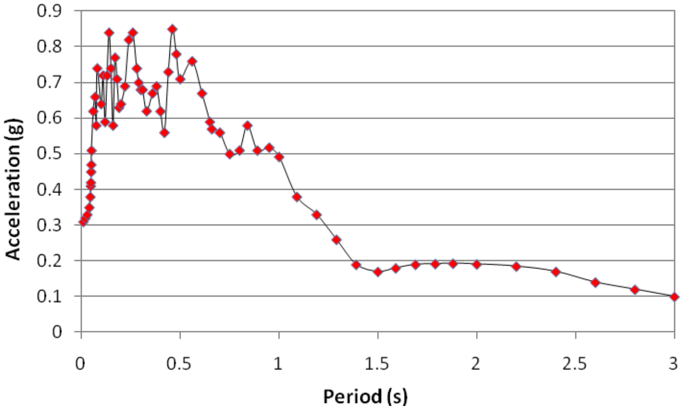
Loading
X , Y acceleration

Mode combination
SRSS

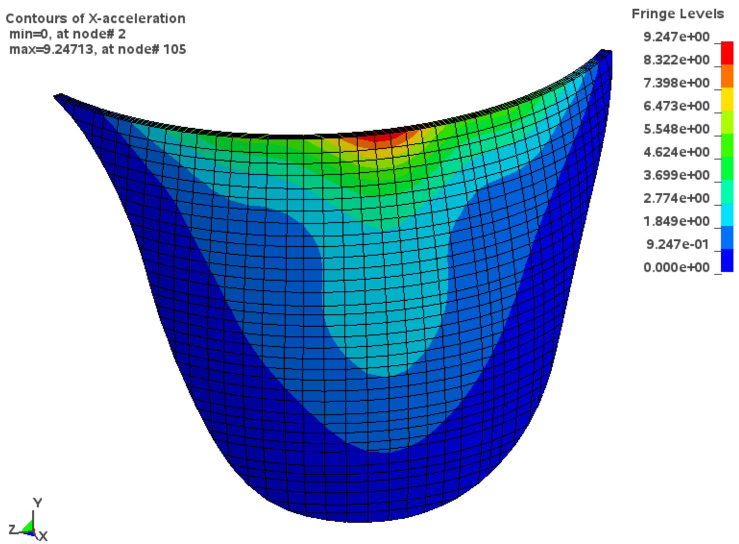
Example: arch dam



- 464.88 feet high
- Rigid foundation
- Subjected to *x*-directional ground acceleration spectrum



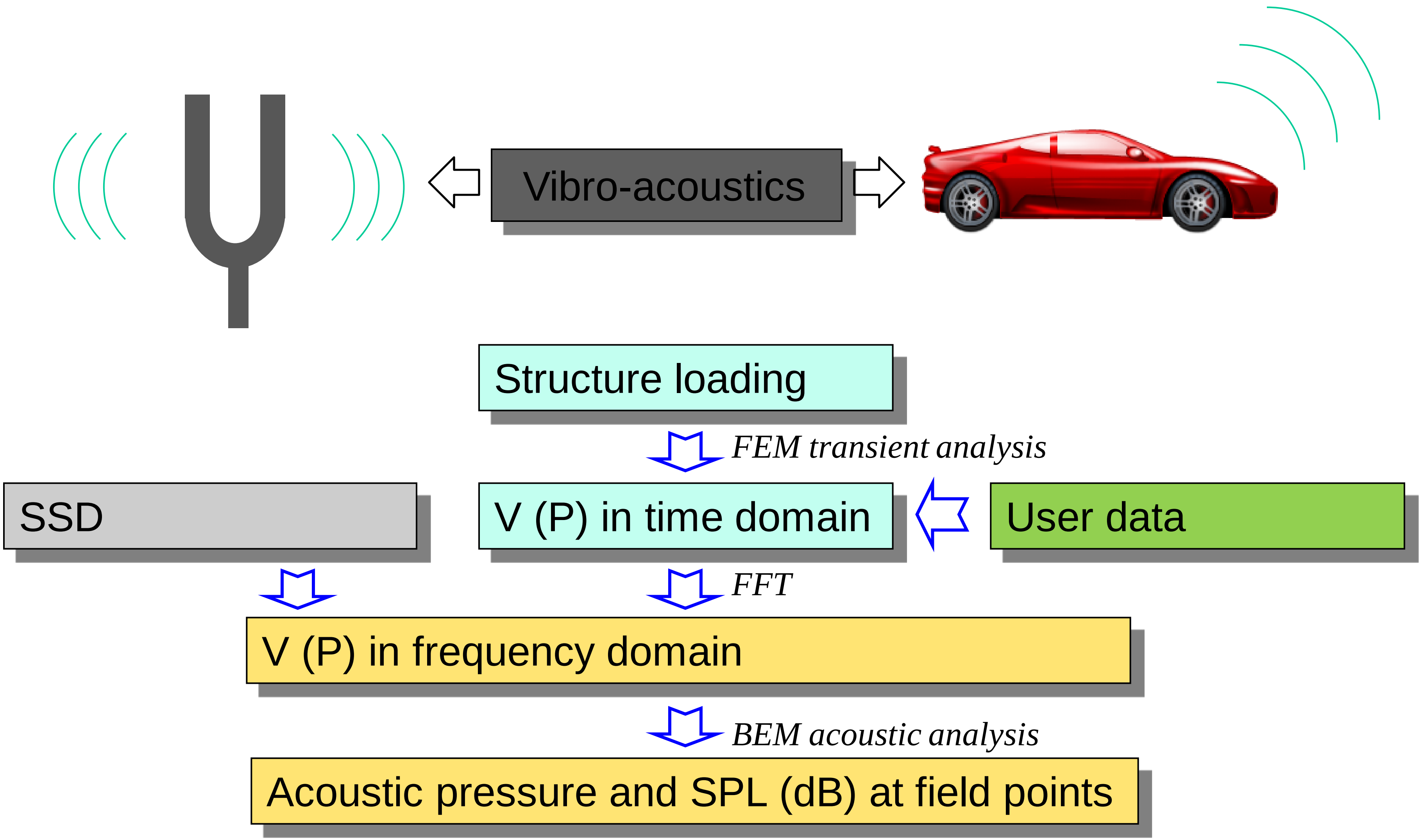
The pseudo-acceleration spectrum of El Centro earthquake ground motion (ζ=5%)



The 1940 El Centro earthquake (or 1940 Imperial Valley earthquake) occurred on May 18 in the Imperial Valley in Southern California near the border of the United States and Mexico. It had a magnitude of 6.9.

6. Acoustic analysis by BEM/FEM

Introduction: vibro-acoustics



FREQUENCY_DOMAIN_ACOUSTIC_BEM_*{OPTION}

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

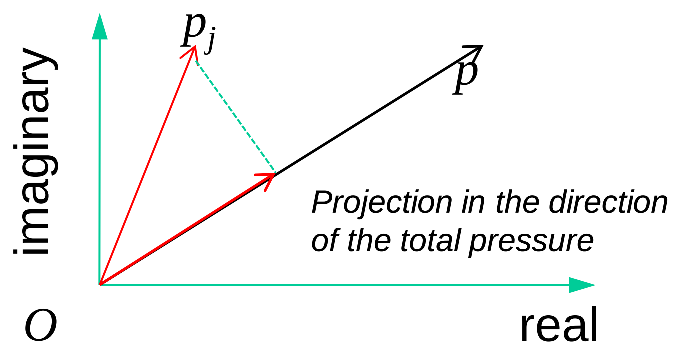
  Assumptions and simplification in formulation

  Very fast since no equation system to solve

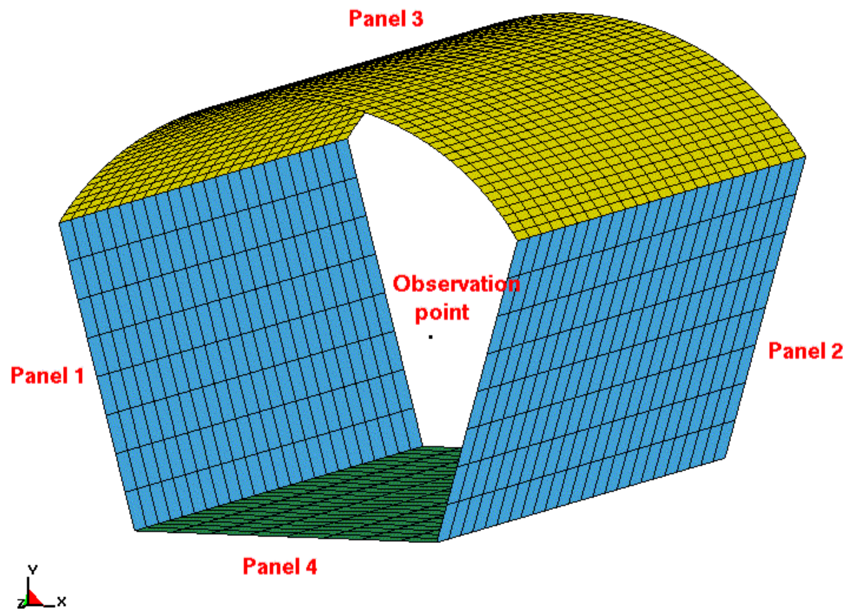
Acoustic panel contribution

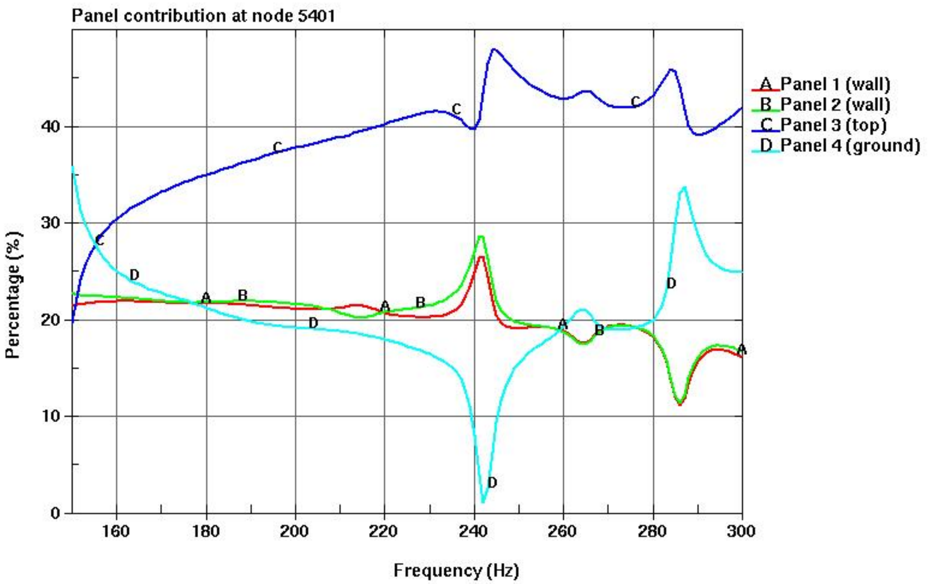
$$p(P) = \sum_{j=1}^{N} \int_{\Gamma_j} \left(G \frac{\partial p}{\partial n} - p \frac{\partial G}{\partial n} \right) d\Gamma_j$$

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



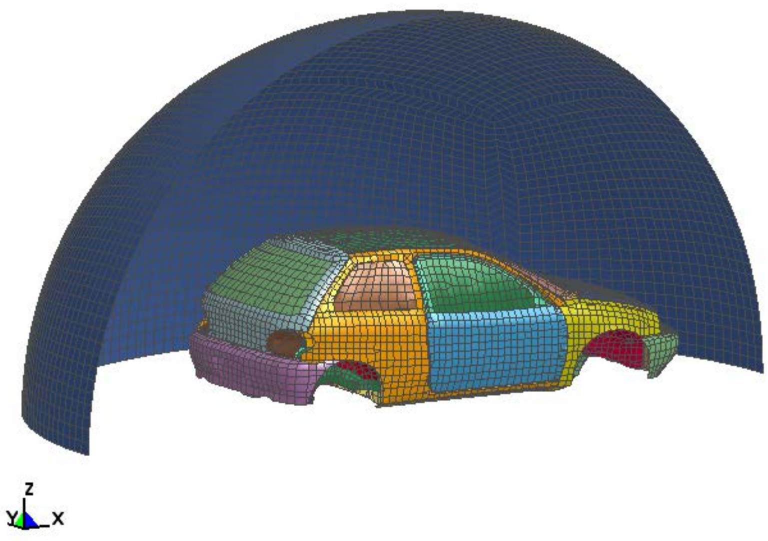
A simplified tunnel model



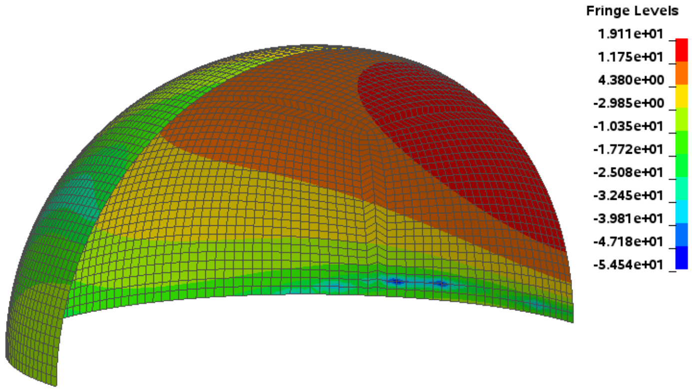


Radiated noise by a car

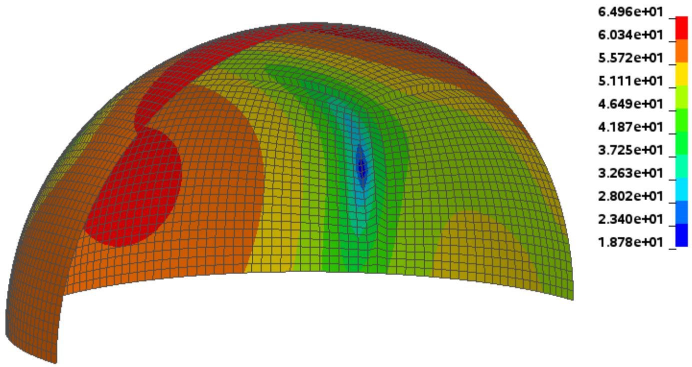
SPL distribution (dB)



An imaginary semi-sphere for better visualization of the noise distribution

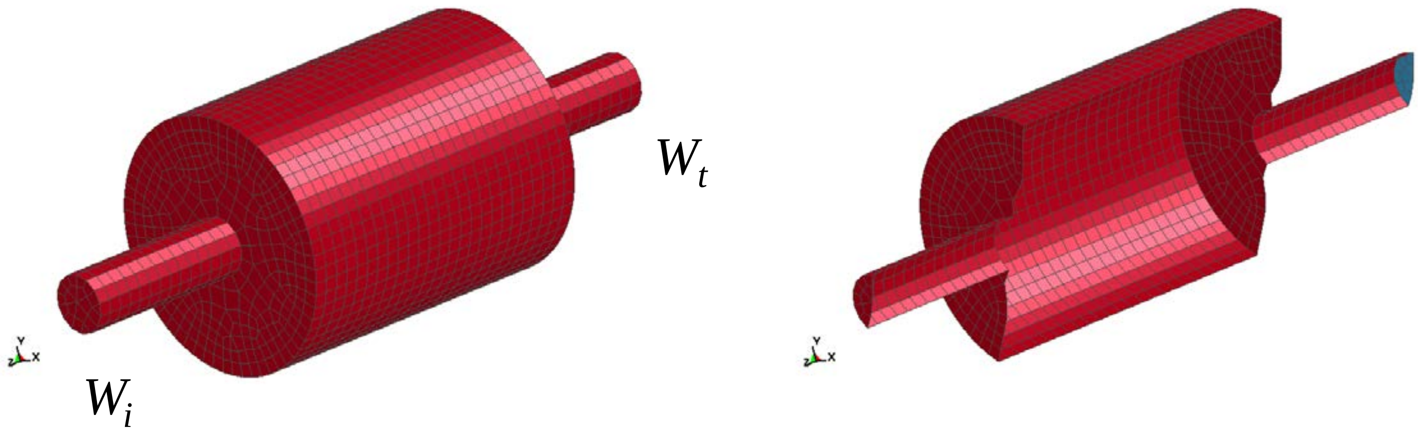


Freq = 11 Hz



Freq = 101 Hz

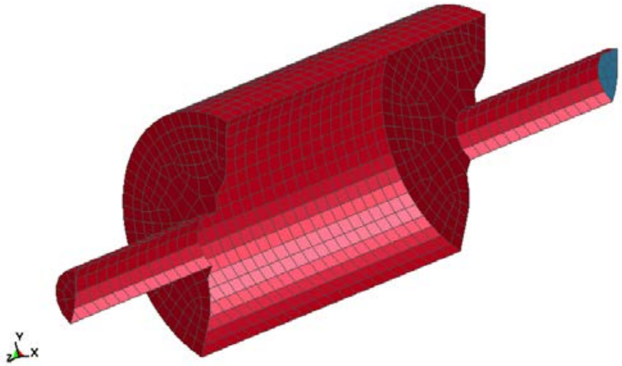
Muffler transmission loss analysis

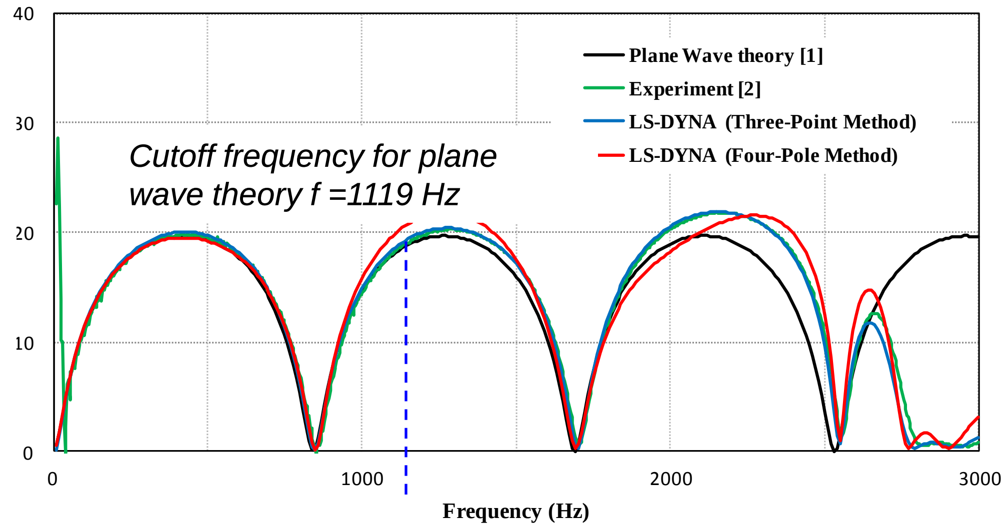


TL (Transmission loss) is the difference in the sound power level between the incident wave entering and the transmitted wave exiting the muffler when the muffler termination is anechoic (no reflection of sound).

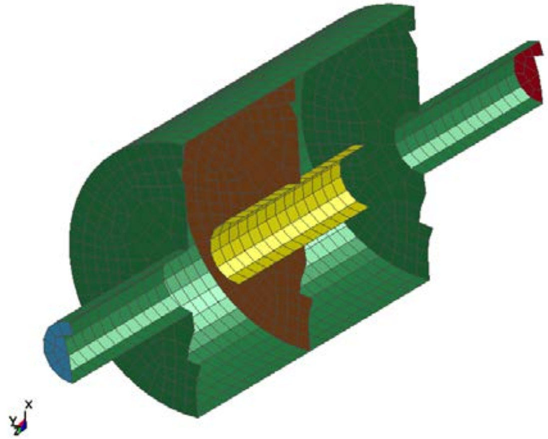
$$TL = 10 \log_{10} \frac{W_i}{W_t}$$

Simple expansion chamber





Double expansion chamber

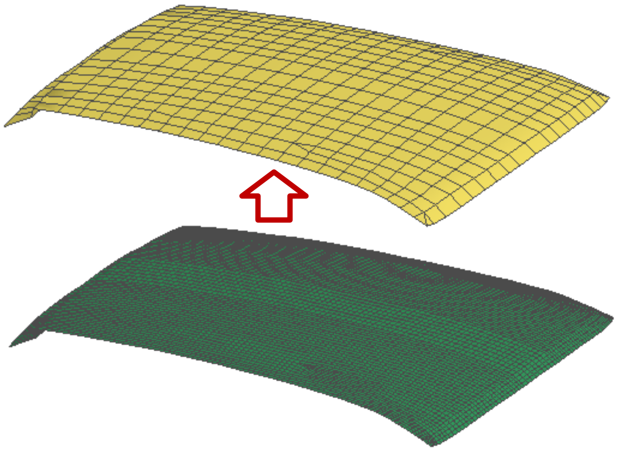


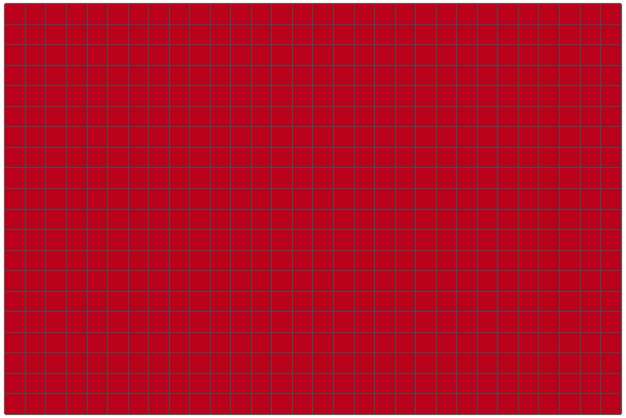
*BOUNDARY_ACOUSTIC_MAPPING

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

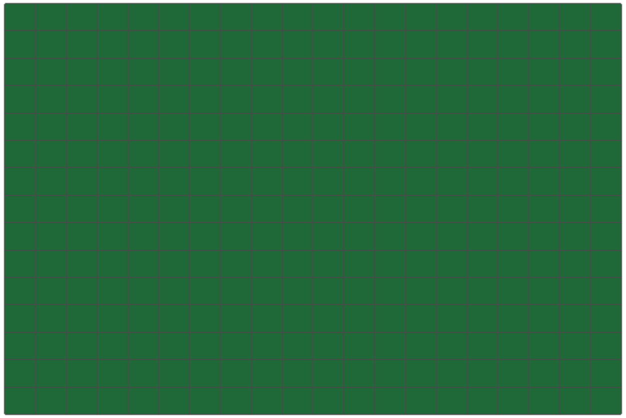
Card	1	2	3	4	5	6	7	8
Variable	SSID	STYP						
Type	I	I						
Default	none	0						

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.

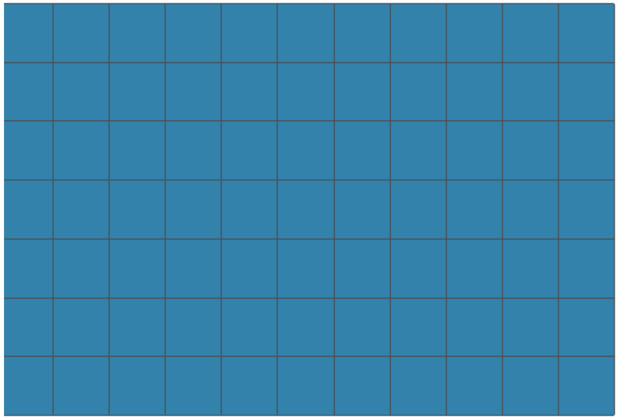




Mesh A: 20 × 30 (600)



Mesh B: 15 × 20 (300)

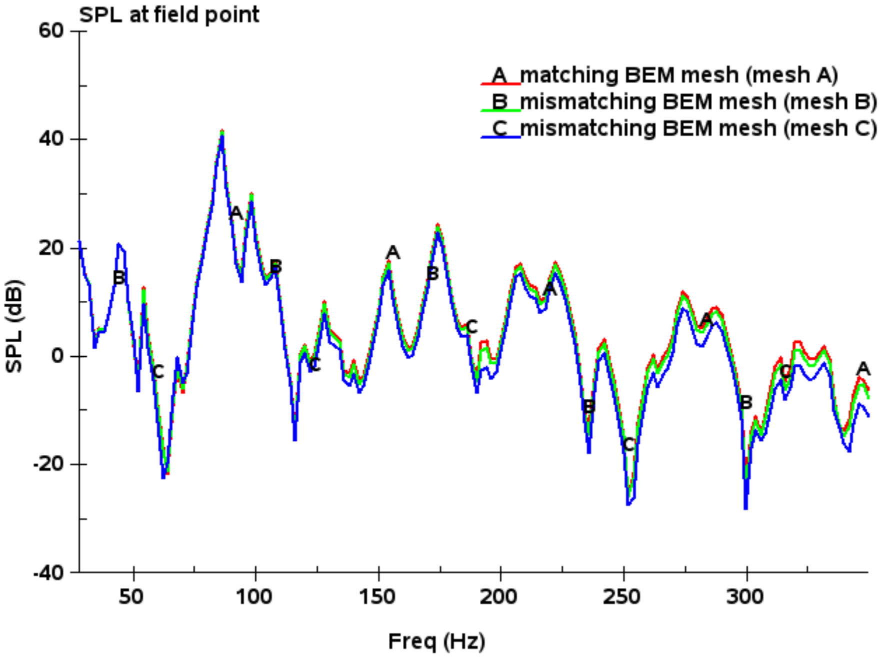


Mesh C: 7 × 11 (77)

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

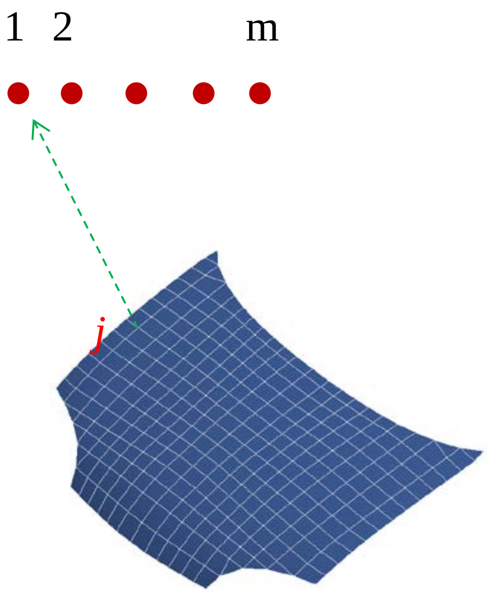


*FREQUENCY_DOMAIN_ACOUSTIC_BEM_*ATV**

- 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

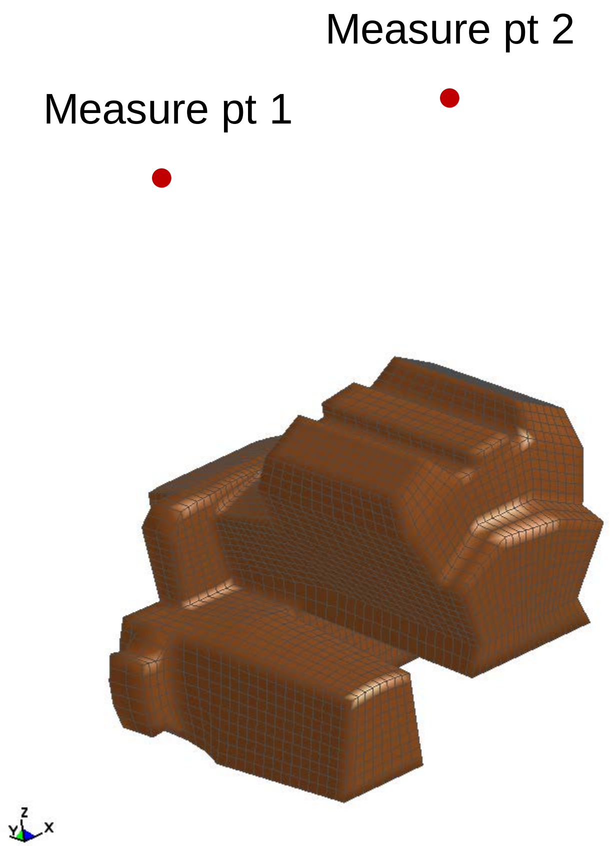
$$\begin{Bmatrix} P_1 \\ P_2 \\ \vdots \\ P_i \\ \vdots \\ P_m \end{Bmatrix} = \begin{bmatrix} \Omega_{1,1} & \Omega_{1,2} & \cdots & \Omega_{1,j} & \cdots & \Omega_{1,n} \\ \Omega_{2,1} & \Omega_{2,2} & \cdots & \Omega_{2,j} & \cdots & \Omega_{2,n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots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



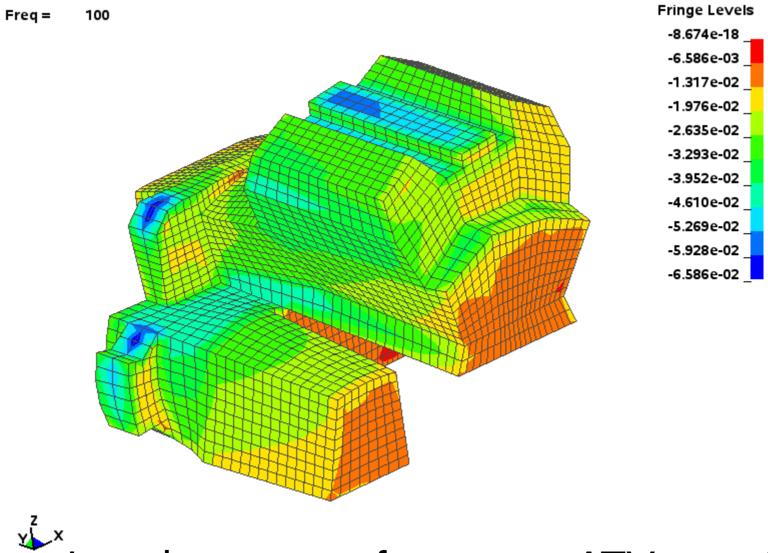
Need to be computed only once

Change from case to case

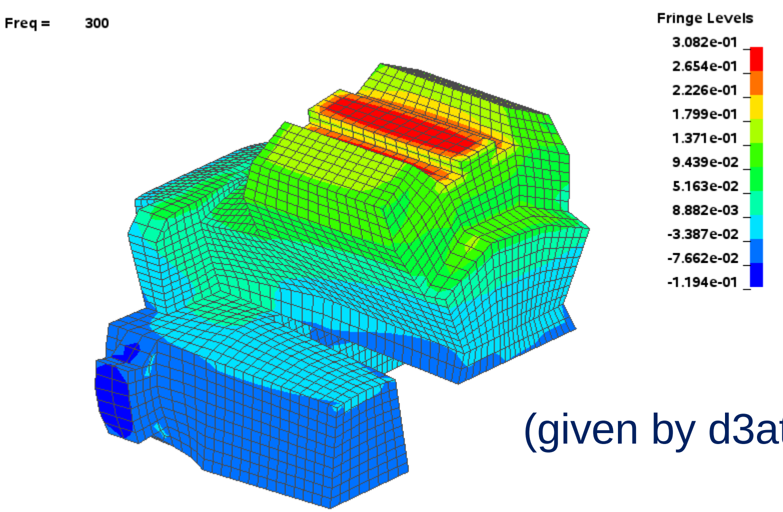
ATV of auto engine model



Real part of pressure ATV at pt 1



Imaginary part of pressure ATV at pt 2



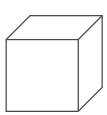
(given by d3atv)

Introduction: FEM Acoustics

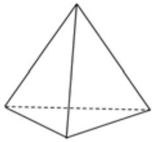
*FREQUENCY_DOMAIN_ACOUSTIC_FEM

- 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.
- Compute acoustic pressure and SPL (sound pressure level)
- Output binary database: d3acs (accessible by LS-PREPOST)
- Output ASCII database: Press_Pa and Press_dB as xyplot files
- Output frequency range dependent on mesh size
- Very fast since
  - ✓ One unknown per node
  - ✓ The majority of the matrix is unchanged for all frequencies
  - ✓ Using a fast sparse matrix iterative solver

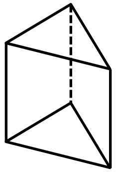
Hexahedron



Tetrahedron



Pentahedron

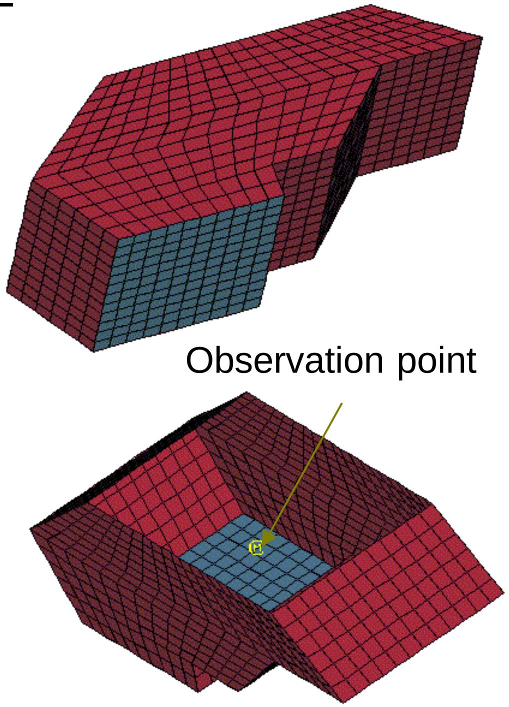


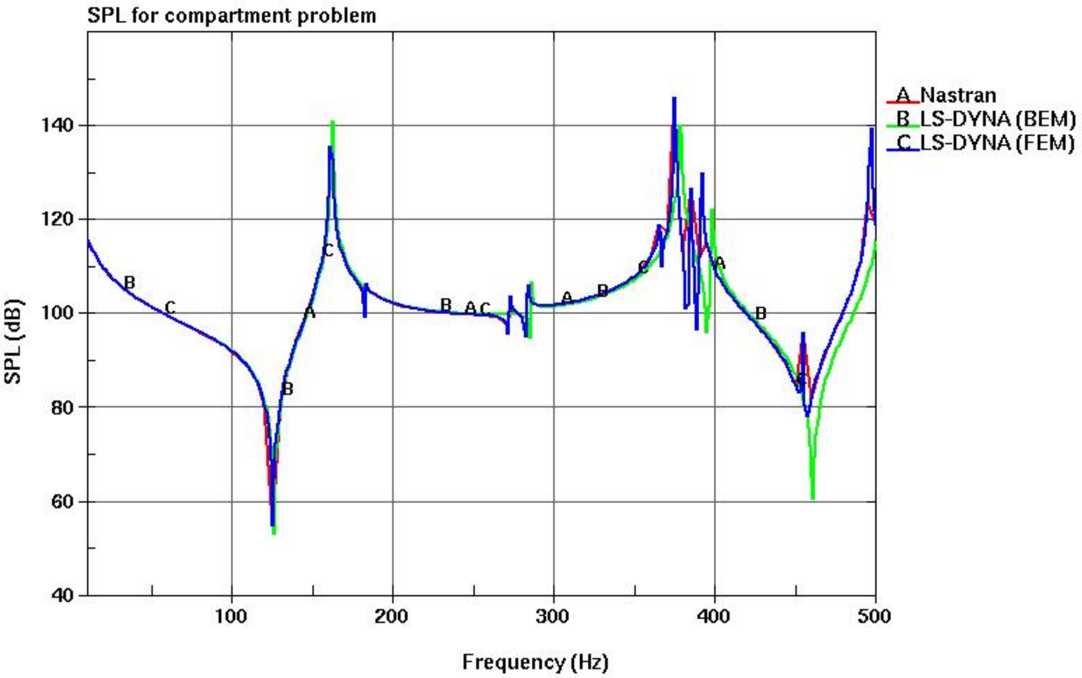
Example: compartment of vehicle

Model information

FEM: 2688 elements

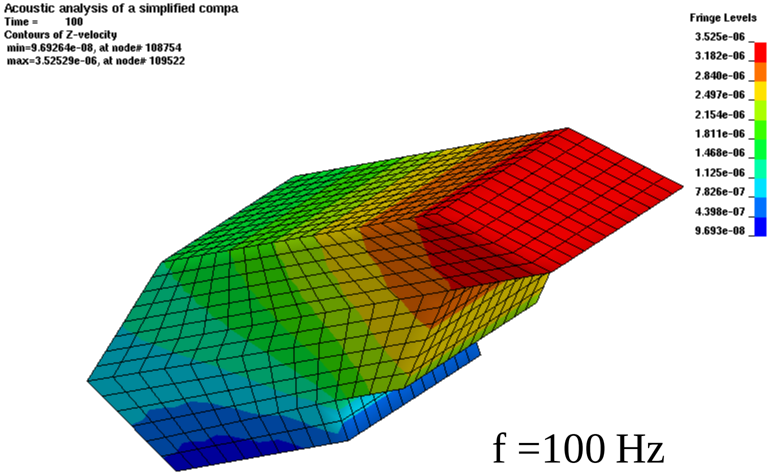
BEM: 1264 elements



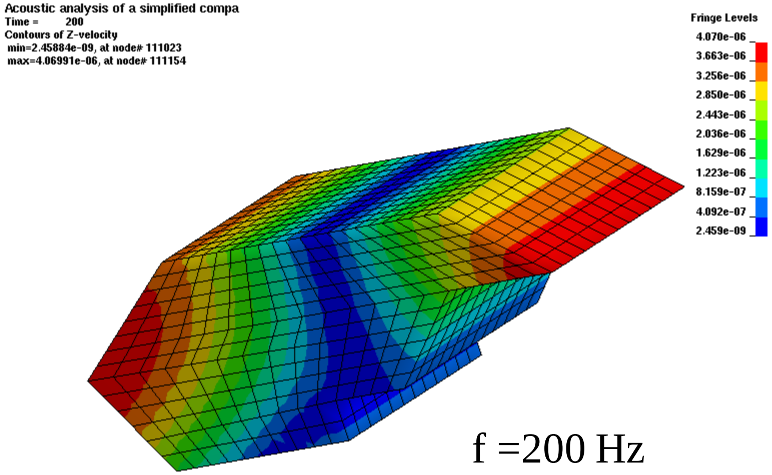


Excitation of the compartment (1.4×0.5×0.6) m^3 by a velocity of 7mm/s

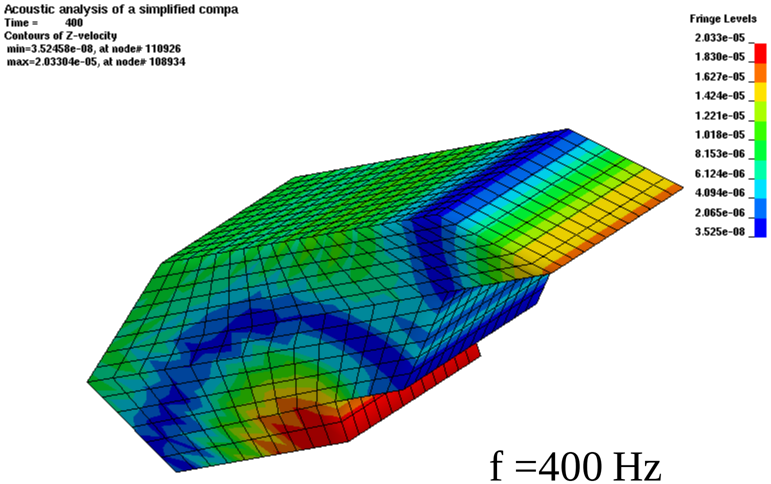
Pressure distribution



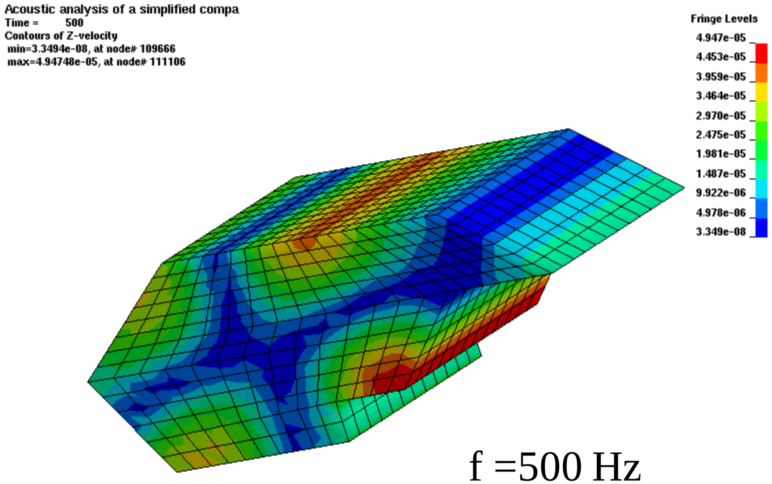
f =100 Hz



f =200 Hz



f =400 Hz



f =500 Hz

(given by d3acs)

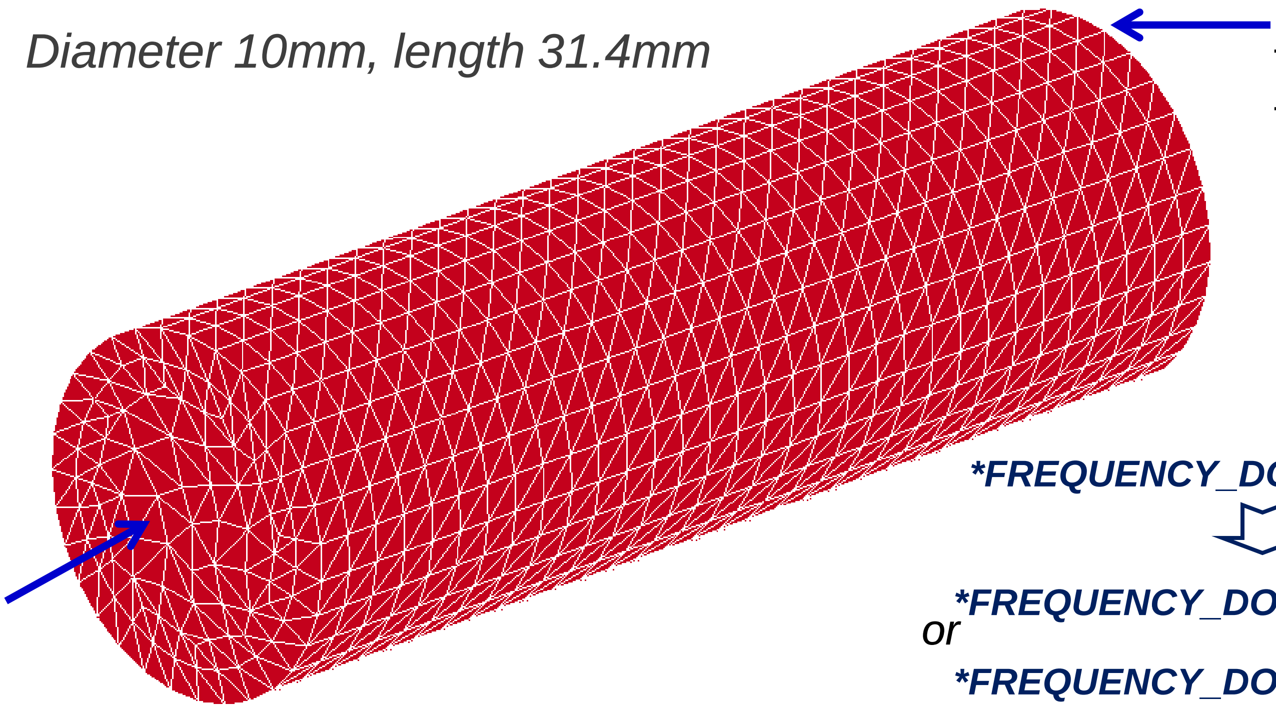
Example: a cylinder model

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**

⇩

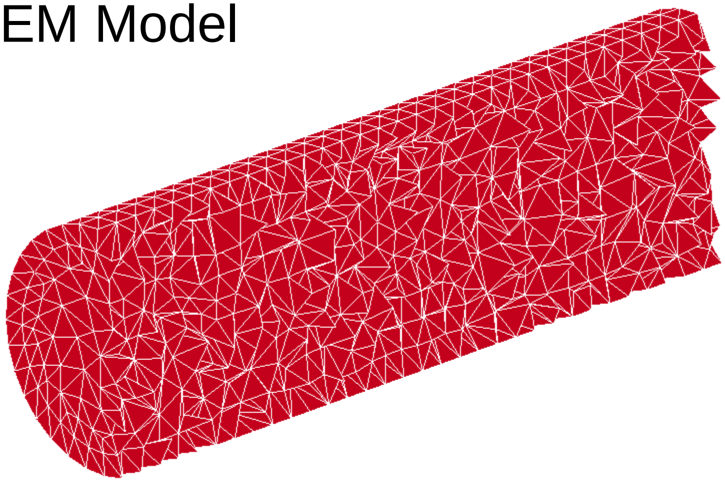
***FREQUENCY_DOMAIN_ACOUSTIC_BEM**

or

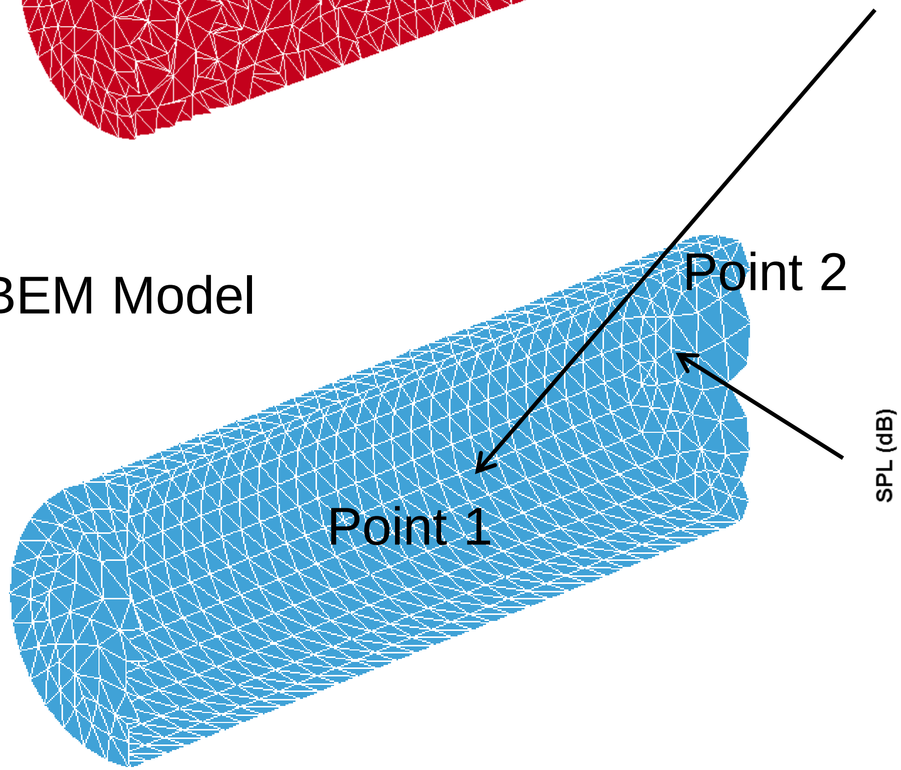
***FREQUENCY_DOMAIN_ACOUSTIC_FEM**

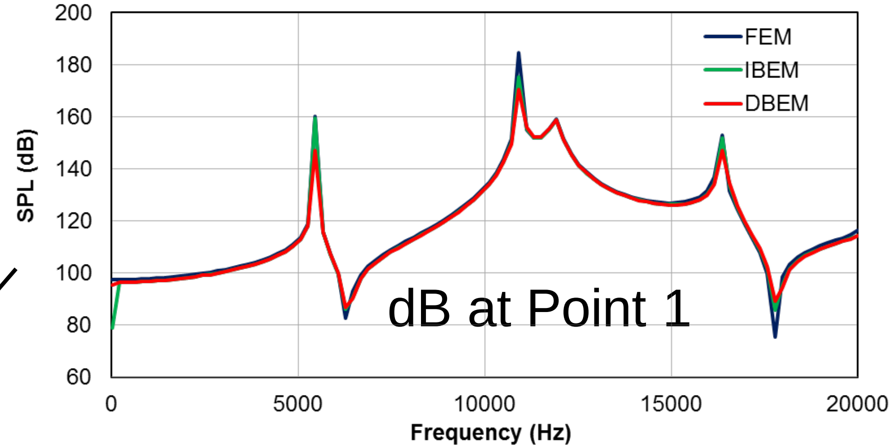
Nodal force 0.01N is applied for frequency range of 10-20000 Hz.

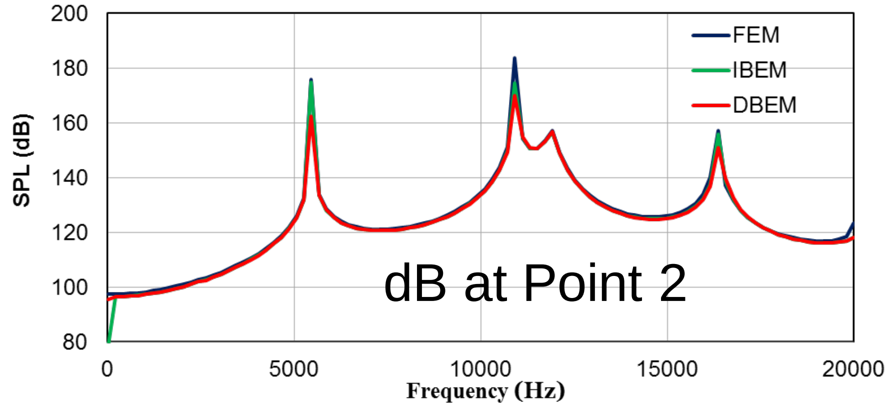
FEM Model



BEM Model

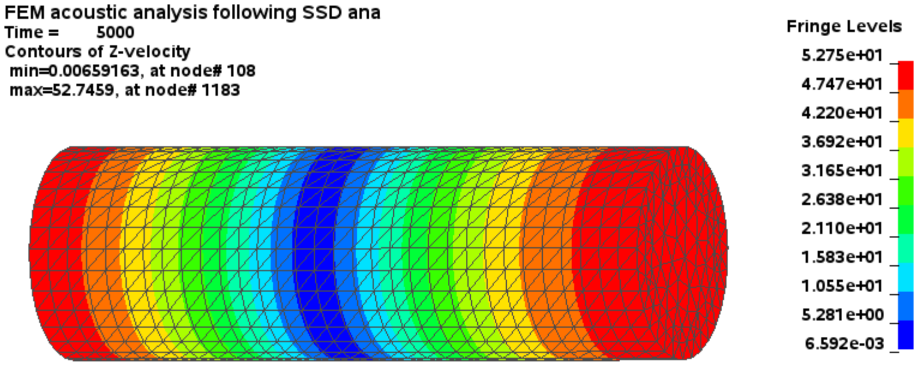




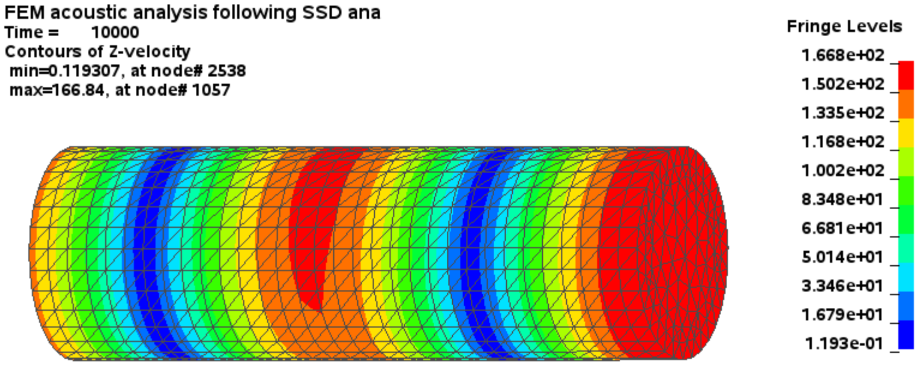


Acoustic pressure distribution

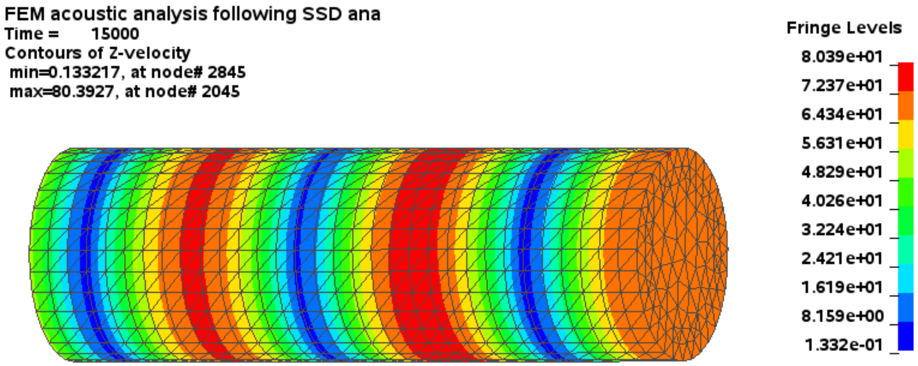
(given by d3acs)



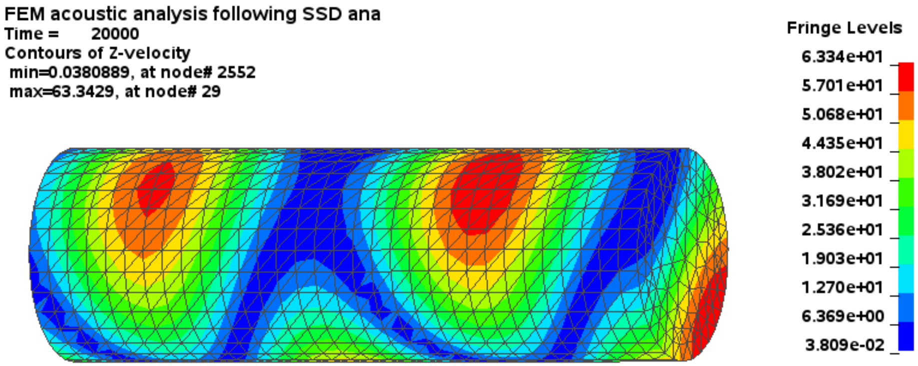
f =5000 Hz



f =10000 Hz



f =15000 Hz



f =20000 Hz

7. Conclusion & future work

A set of frequency domain features have been implemented, towards NVH, durability analysis of vehicles and other vibration and acoustic analysis

- ✓ Frequency Response Function
- ✓ Steady State Dynamics
- ✓ Random Vibration & Fatigue
- ✓ Acoustic analysis by BEM/FEM
- ✓ Response spectrum analysis

Future work

- SEA method for high frequency acoustics
- Fast multi-pole BEM for acoustics
- Infinite acoustic FEM
- Fatigue analysis with strains
- Feedbacks and suggestions from users

Acknowledgements:

- CIMES, France
- Jaguar Landrover, UK
- JSOL, Japan
- NCAC, USA
- Parker Hannifin Corporation, USA
- Predictive Engineering, USA
- Rafael, Israel

Thank you!