LS-DYNA®'s NVH solvers and their applications

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Ansys

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    - Frequency domain boundary element method
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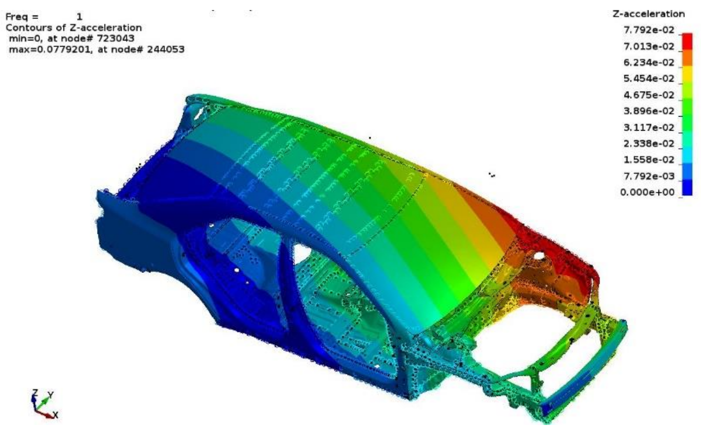
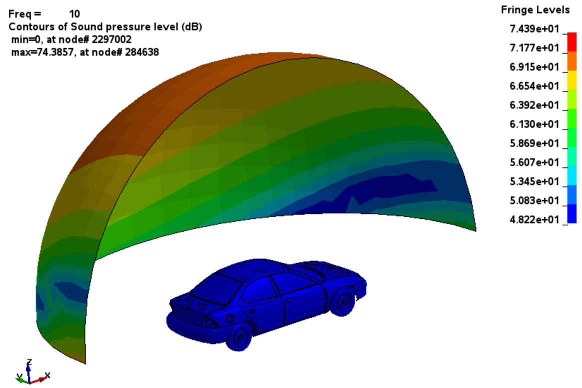
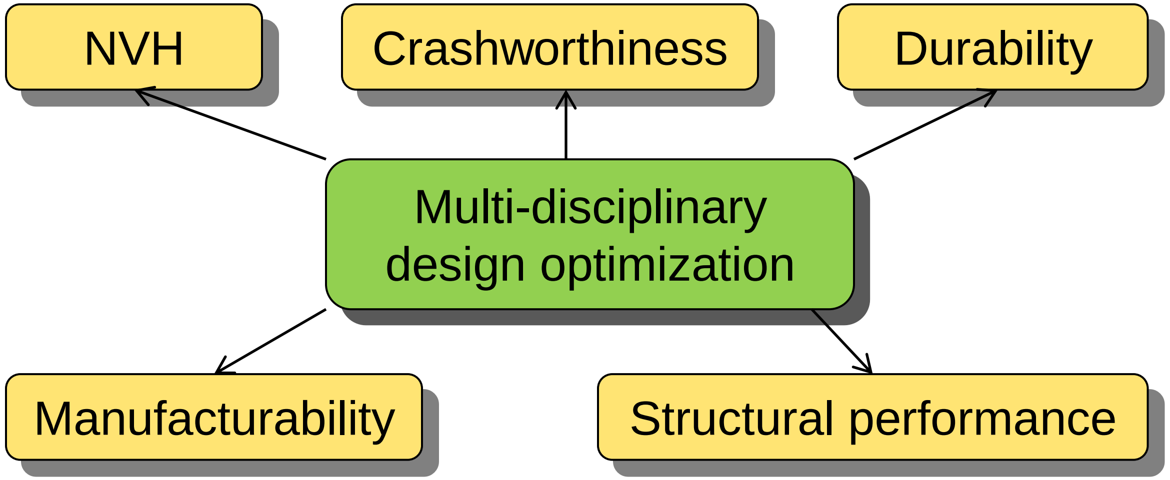


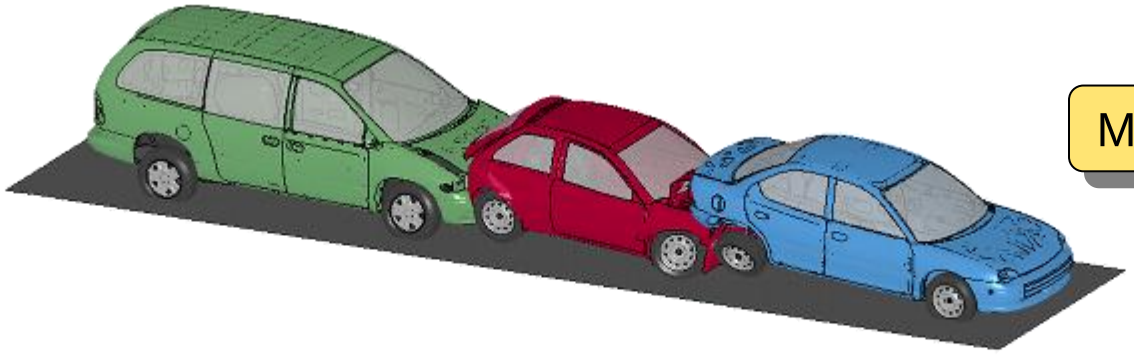


Overview of the NVH solvers in LS-DYNA

Motivation

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





NVH solvers in LS-DYNA

Eigensolvers

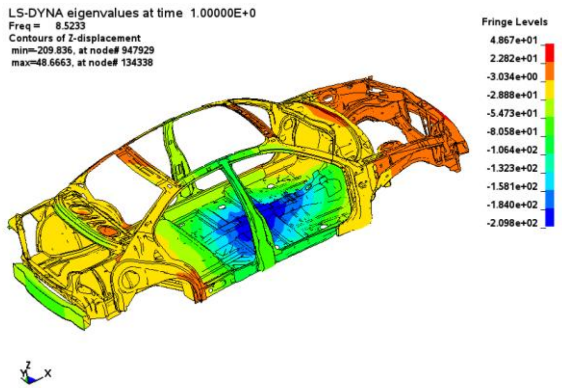
- Lanczos
- MCMS
- LOBPCG
- Fast Lanczos
- Intermittent eigenvalue
- Pre-stressed eigenvalue

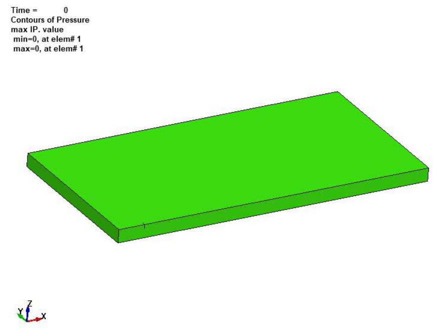
Vibration solvers

- FRF
- SSD
- Random Vibration
- Response Spectrum Analysis
- DDAM

Acoustic solvers

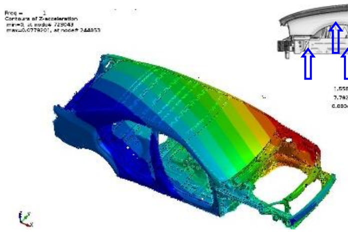
- Transient acoustics (FEM)
- Frequency domain BEM
- Frequency domain FEM
- Acoustic eigenvalue analysis
- Spectral element method
- Modal acoustics
- Statistical Energy Analysis
- Perfectly Matched Layer

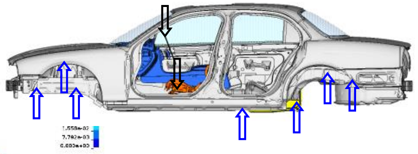


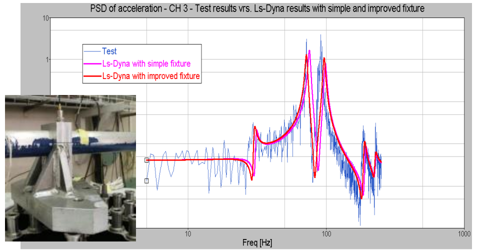


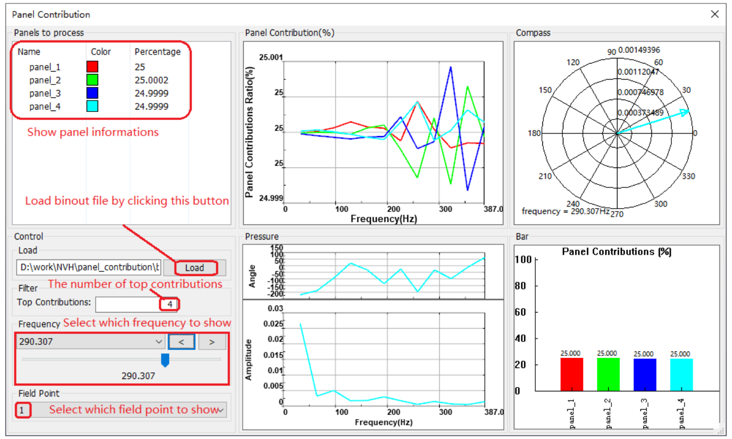
Capabilities

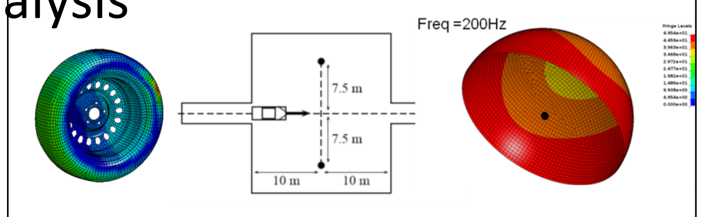
- Full body, trimmed body, BIW global modes (torsion & bending), dynamic stiffness, equivalent static stiffness, effective mass, etc.
- Shaker table testing simulation
  - Harmonic vibration (sine sweep)
  - Random vibration
- Vibration analysis with pre-stress
- Acoustic panel contribution analysis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



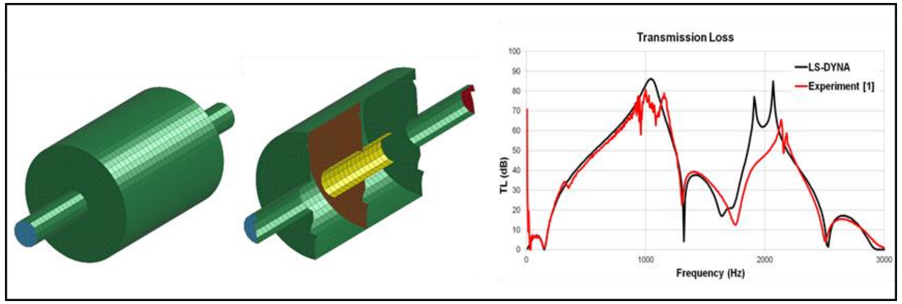






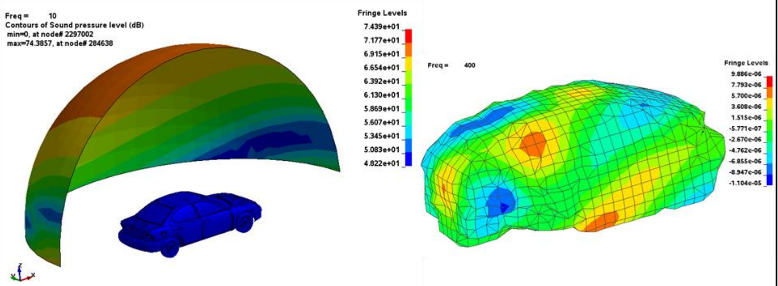


Pass-by noise test based on ISO 362 Standard

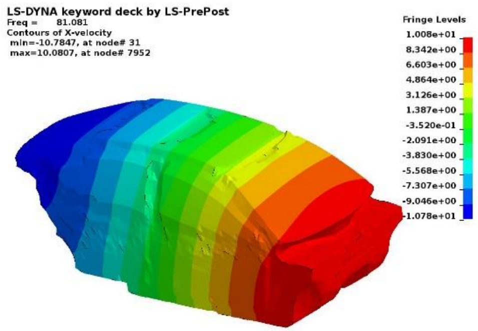


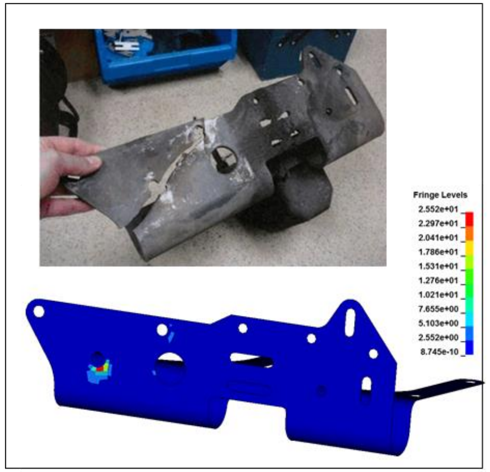
Capabilities

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

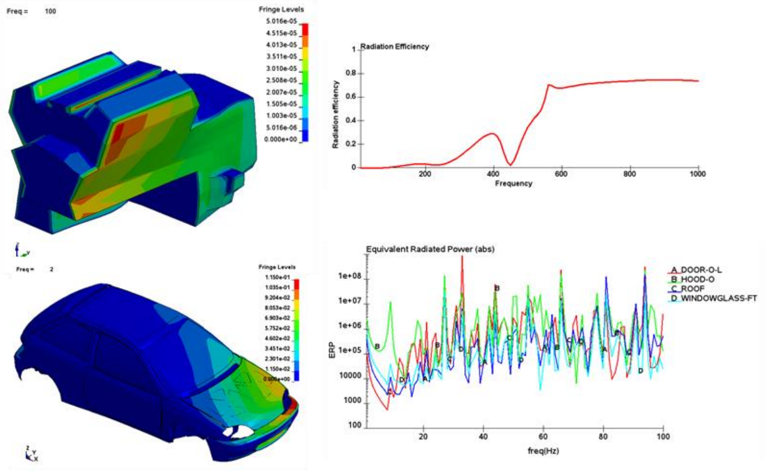


BEM works for both exterior and interior acoustics



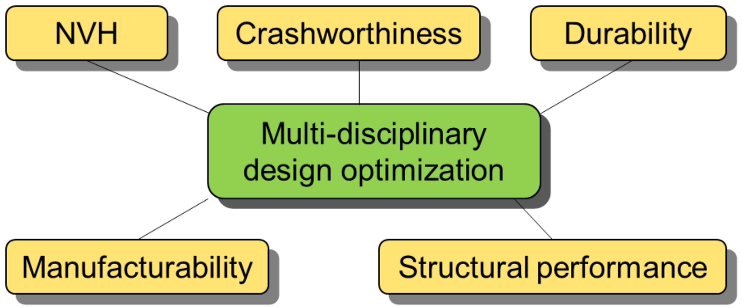


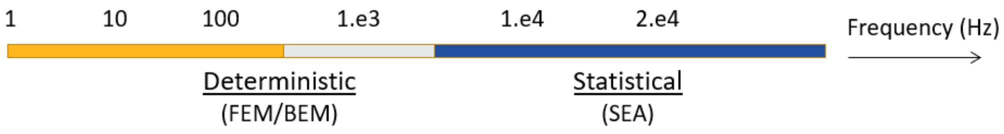
ERP and radiation efficiency



Features

- A common model approach
  - based on LS-DYNA crash analysis model
  - save model conversion / translation
  - facilitate multidisciplinary design optimization
- A complete suite of acoustic analysis methods (FEM, BEM, SEA, SEM, ERP, etc.)
  - From time domain to frequency domain
  - From low frequency to high frequency
  - From interior to exterior
  - From near field to far field
- Seamless coupling / integration with other Multiphysics solvers in LS-DYNA



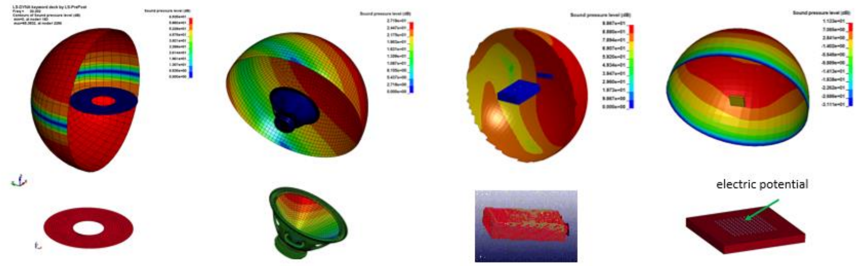


Spinning disc noise: coupling with rotor dynamics solver (Liping Li, Roger Grimes)

Speaker sound: coupling with EM solver (Pierre L'Eplattenier, Inaki Caldichoury)

Tank sloshing noise: coupling with ALE solver (Hao Chen, Nicolas Aquelet, Ian Do)

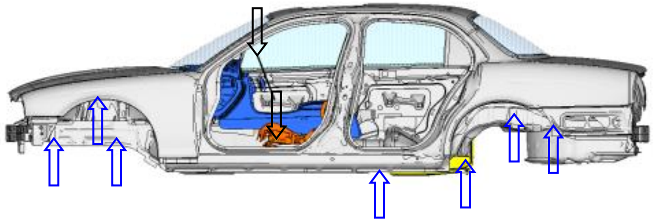
Piezo acoustics: coupling with PZT solver (Isheng Yeh, Xiaomeng Tong)



Vibration solvers and their application

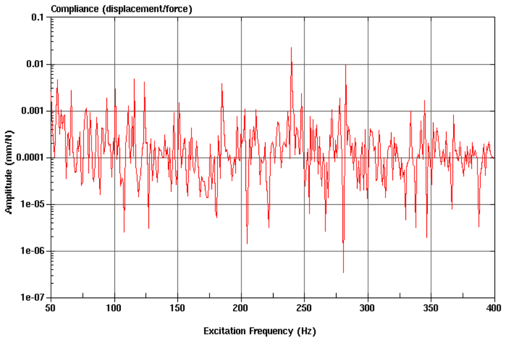
*FREQUENCY_DOMAIN_FRF

FRF (Frequency Response Function) calculates transfer function between load and dynamic response of a system, for a specified range of frequency. FRF curves are composed of amplitude and phase angle of transfer function. Pre-stress condition can be considered. Multiple subcases can be included in one run, using the option _SUBCASE.



FRF can help to

- locate load transfer path or energy flow for road/engine excitations
- estimate structural properties such as dynamic stiffness, effective mass
- provide basis for frequency response analysis



Application cases

Modal frequency response analysis
in LS-DYNA
- Application on a BIW railway car

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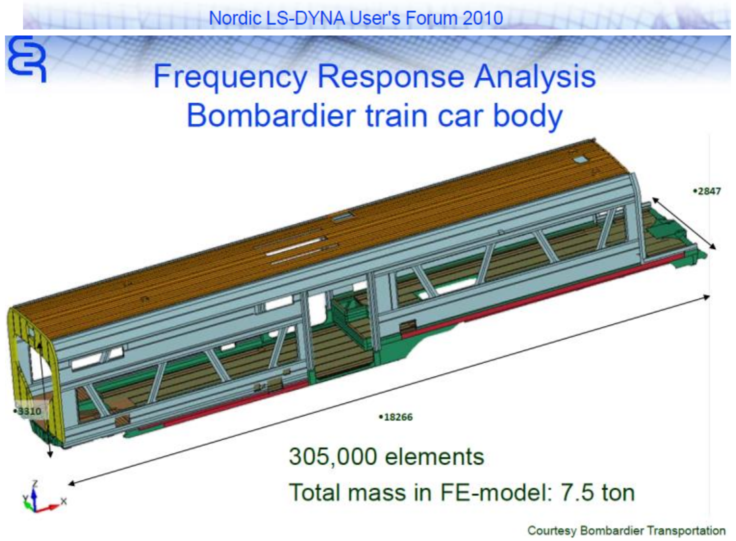
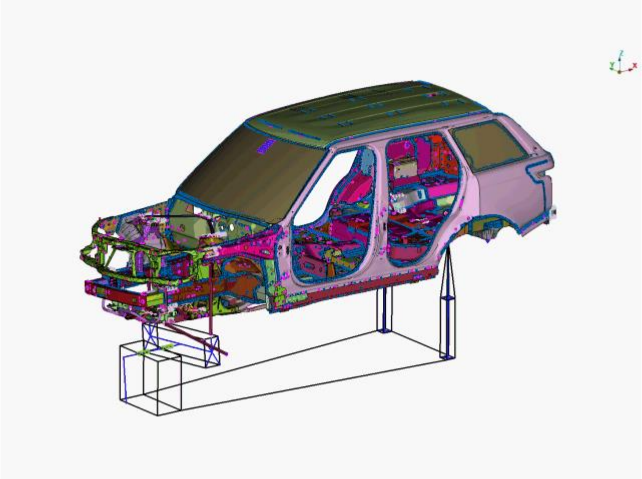
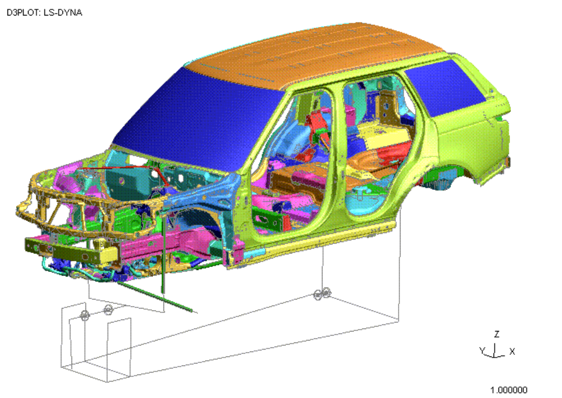


The Use Of LS_DYNA for Body NVH
"The Success So Far "

Tayeb Zeguer, Bindu Ali

Static Torsion





Optistruct (AMLS) Torsional Stiffness = 28.3 kNm/deg

Dyna Torsional Stiffness = 29.7 kNm/deg (Type 1 Solids)

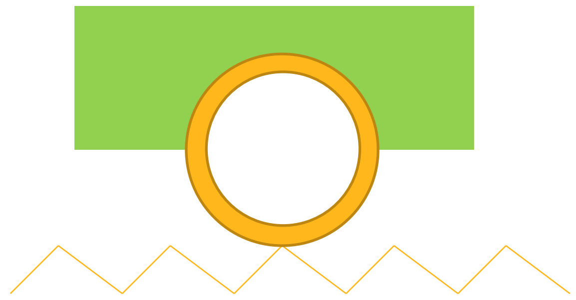
Nastran Torsional Stiffness = 27.8 kNm/deg

Dyna Torsional Stiffness = 30.7 kNm/deg (Type 2 Solids)

*FREQUENCY_DOMAIN_SSD

$$F(t) = F_0 \sin(\omega t + \phi)$$

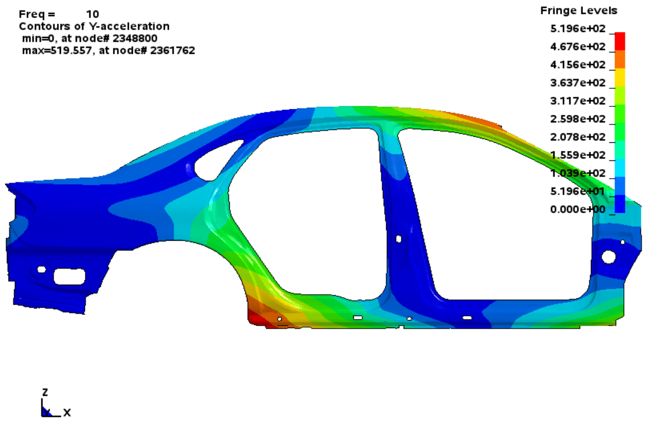
SSD (steady state dynamics), provides structural response under harmonic or steady state vibration load, e.g. sine sweep. The results, which are dependent on frequencies, include magnitude and phase angle of nodal and elemental response.



Typical harmonic excitation

Features:

- Modal contribution ratios available.
- Integrated vibro-acoustic and vibro-fatigue analysis.
- Multiple subcases in one run, using the option _SUBCASE.
- Both mode-based method and direct method are available

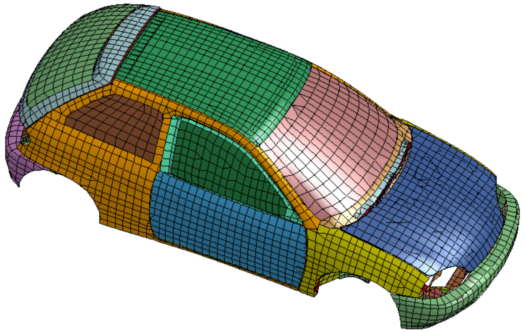


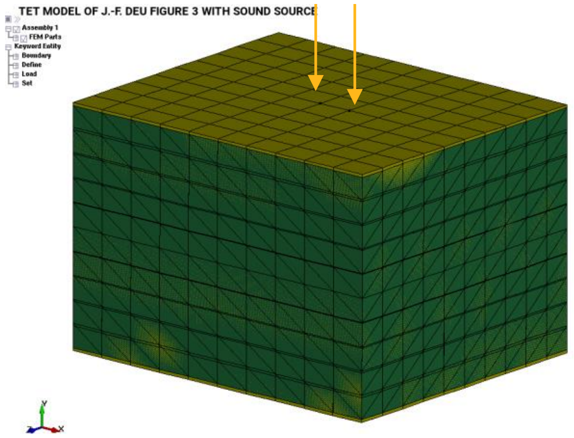
Acceleration response of an auto side frame under harmonic excitation

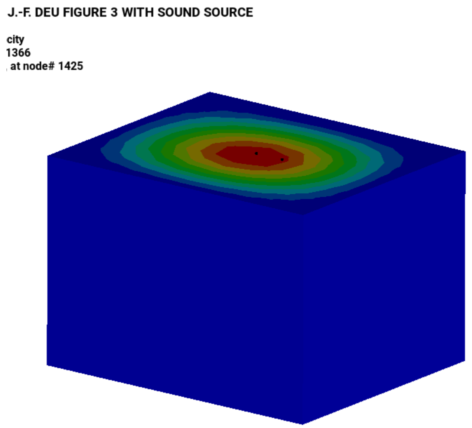
*CONTROL_IMPLICIT_SSD_DIRECT for coupled analysis

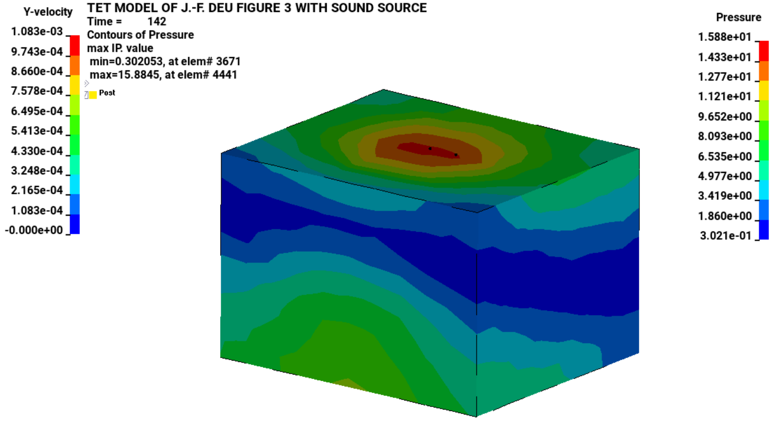
- Direct, complex solution to steady state vibration of coupled acoustic fluid and structure system
- Acoustic solid element ELFORM 8 and 14 can be used
- Acoustic spectral element can be used
- The coupling of the acoustic fluid and the structural elements is achieved with *BOUNDARY_ACOUSTIC_COUPLING_MISMATCH or by merging acoustic and structural nodes with compatible element faces
- Useful for the cases when interaction between the fluid and the structure need to be considered
- Developed with Roger Grimes and Francois-Henry Rouet.

Nodal force excitation (75-500 Hz)



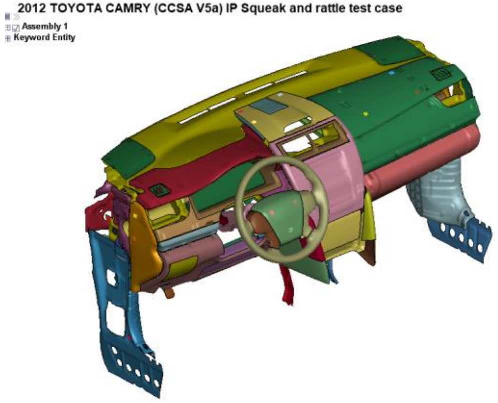




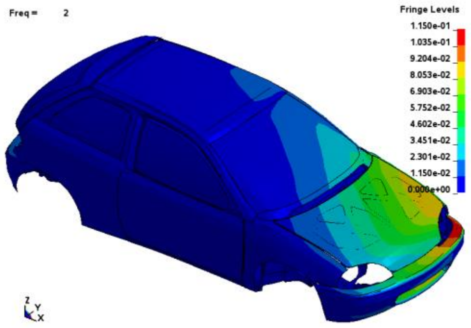


Application cases

- What can we do with SSD results?
  - Acoustic analysis with BEM or FEM
  - Fatigue analysis (sine sweep)
  - Equivalent radiated power (d3erp)
  - BSR (Buzz, Squeak and Rattle)



BSR analysis based on d3ssd (Philip Ho, Anders Jernberg)



d3erp: ERP density plot

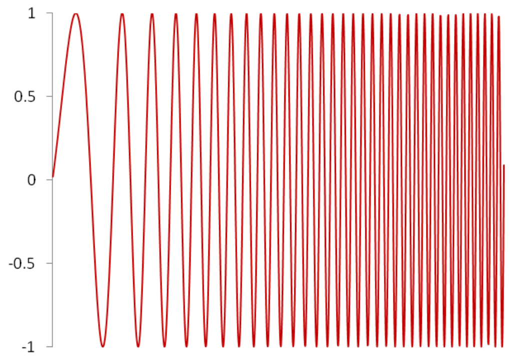
*FREQUENCY_DOMAIN_SSD_FATIGUE

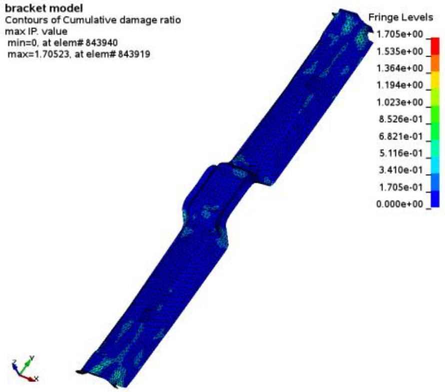
Loading condition

Freq (Hz)	Acl (g)	Duration (min)
16	0.5	12
20	0.5	12
25	0.5	12
31.5	0.5	12
…	…	…
2000	0.5	12

SN fatigue curve

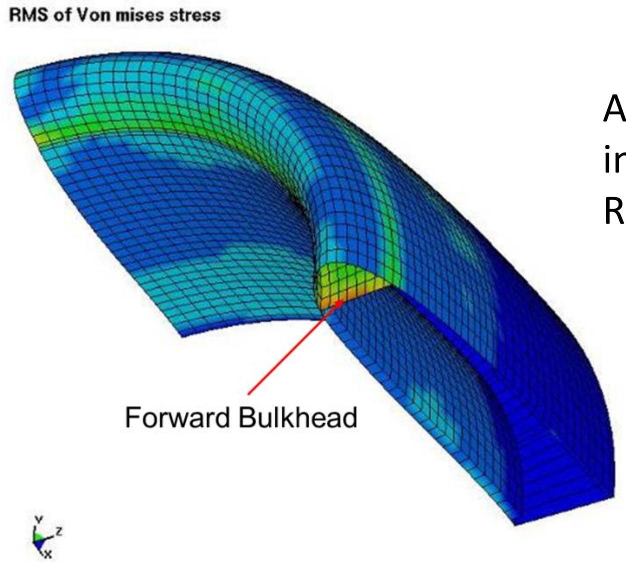
σ (MPa)	N
100	8×10^4
10	8×10^5
1.	8×10^6
0.1	8×10^7
0.01	8×10^8





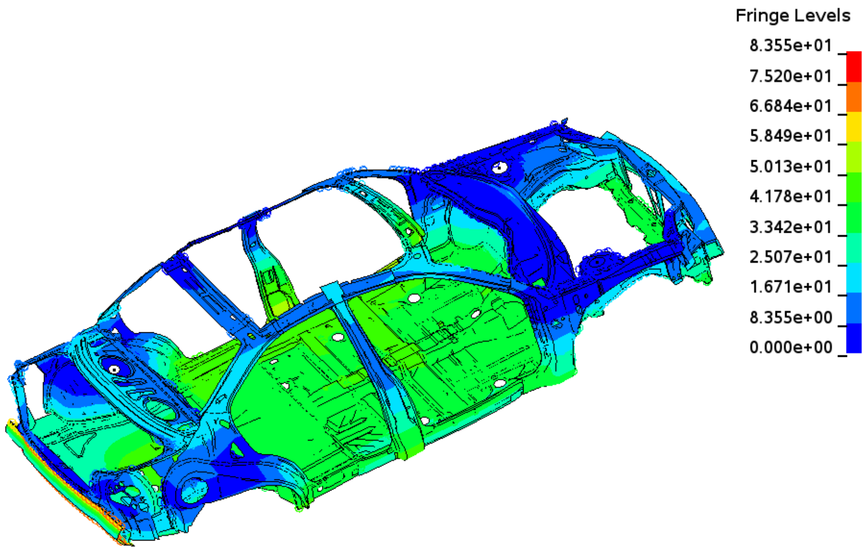
*FREQUENCY_DOMAIN_RANDOM_VIBRATION

Random vibration is motion which is non-deterministic, meaning that future behavior cannot be precisely predicted. LS-DYNA can run random vibration analysis based on load PSD input or time history input and provide PSD and RMS of nodal and elemental responses. The results are given in binary plot databases D3PSD and D3RMS, accessible to LS-PREPOST. RMS results are not affected by frequency resolution in PSD response.



A quarter engine inlet model under Reverberant wave

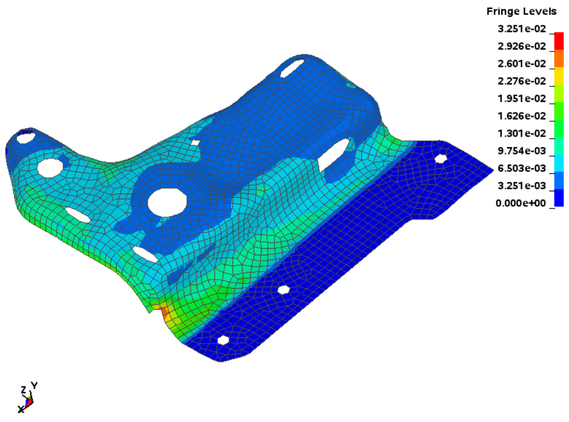
Boeing: Mostafa Rassaian, Yun Huang, JungChuan Lee, Thomas T. Arakawa, "*Structural Analysis with Vibro-Acoustic Loads in LS-DYNA®*", 10th International LS-DYNA Users Conference, 2008.



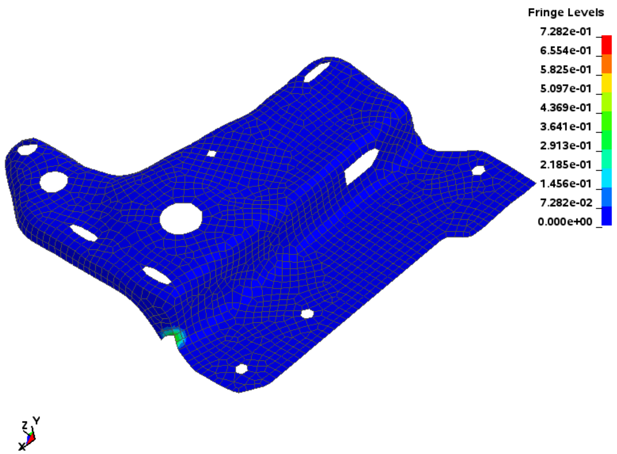
RMS Ux of a BIW model (by d3rms)

*FREQUENCY_DOMAIN_RANDOM_VIBRATION_FATIGUE

- Can run based on FEM or IGA (Stefan Hartmann, Dave Benson)
- Provide cumulative damage ratio and expected life
- Based on Miner's rule of cumulative damage ratio (linear)
- Mean stress correction is available



RMS of Von-Mises stress (GPa)



Accumulative damage ratio

13th European LS-DYNA Conference 2021, Ulm, Germany

Prediction of fatigue damage by random vibration using isogeometric and finite element analysis

Shubiao WANG[1], Renata Troian[1], Leila Khalij [1]

[1]INSA Rouen Normandy, France

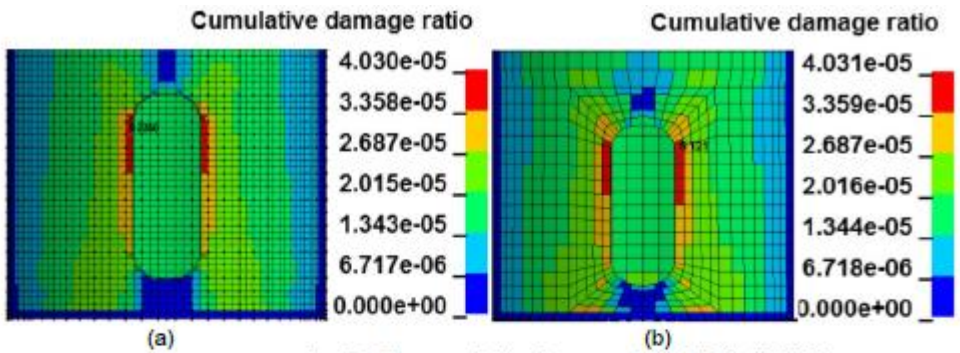
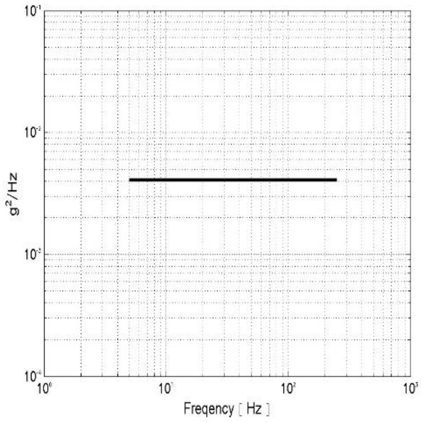


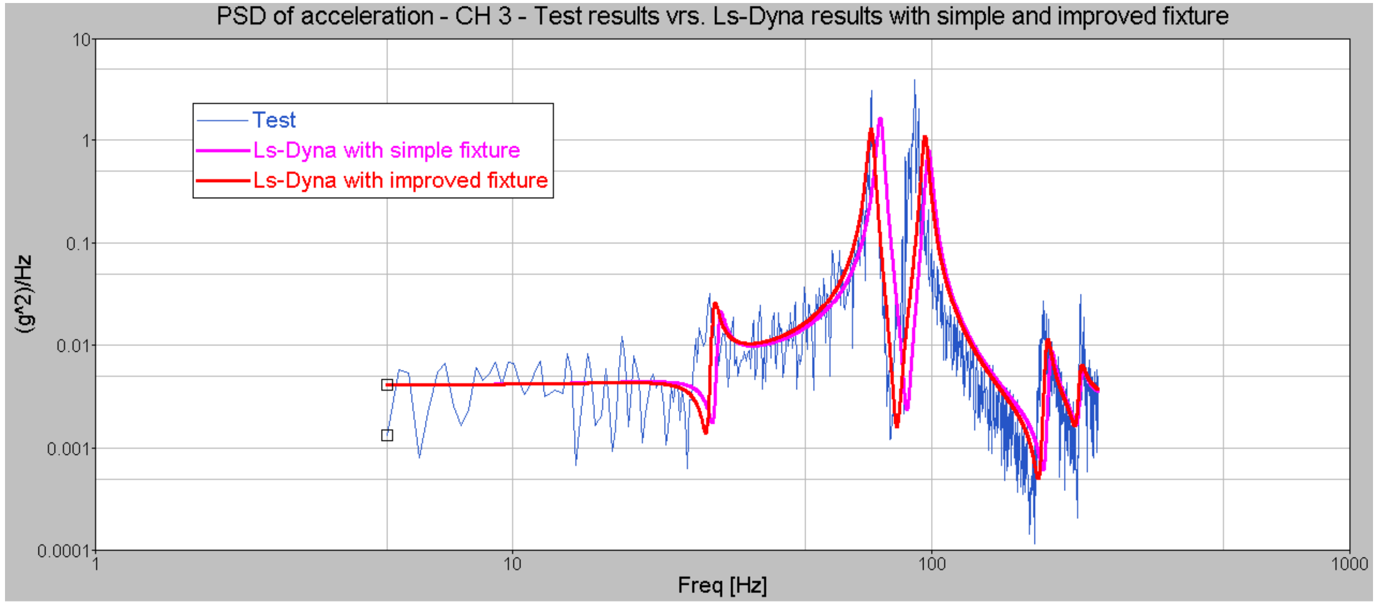
Fig. 20: The cumulative damage ratio (a) IGA; (b) FEA.

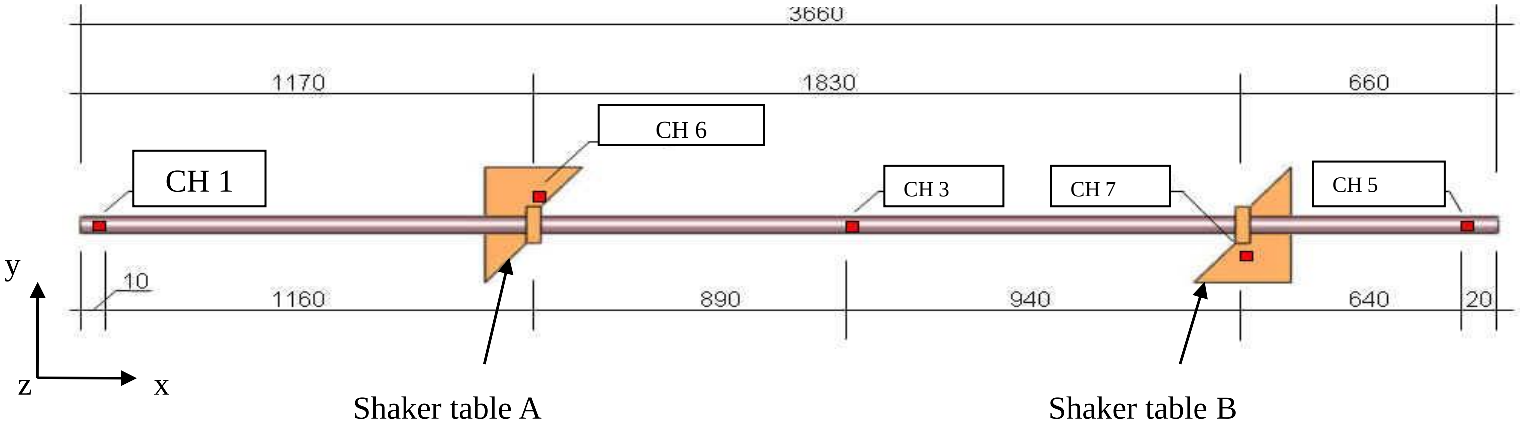
Application cases



Total : 1.00 [Grms]

No.	Freq.	g²/Hz
1	5	0.004082
2	250	0.004082





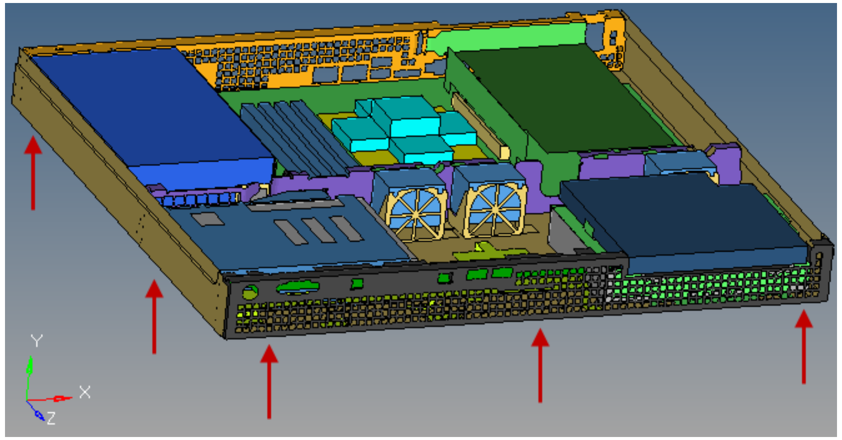
Rafael, Israel: Shor, O., Lev, Y., and Huang, Y., "*Simulation of a Thin-Walled Aluminum Tube Subjected to Base Acceleration Using LS-DYNA's Vibro-Acoustic Solver*", 11th International LS-DYNA Users Conference, Dearborn, Michigan, June 2010.

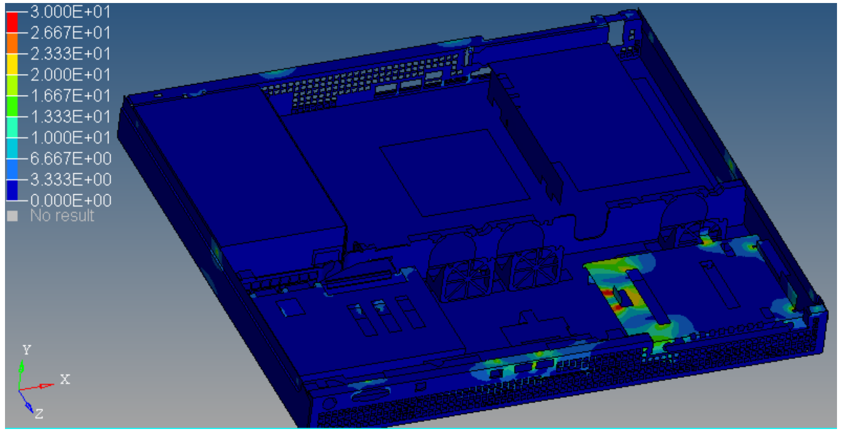
Application cases

- A cluster server is analyzed by LS-DYNA to understand the location of vibration damage under standard random vibration condition
- It is found that the 3σ Von-Mises stress is less than the yield stress of the material (176 MPa).

Maximum values		
	1σ	3σ
U (mm)	0.78	2.34
Sv-m (MPa)	41.2	123.6

GRMS = 1.63 g	
Hz	g^2/Hz
10	0.001
20	0.003
40	0.003
80	0.02
120	0.02
200	0.0015
500	0.0015



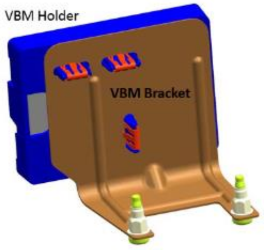


Application cases

15th International LS-DYNA® Users Conference — NVH

Random Vibration Fatigue Life Simulation of Bolt-on Metal Brackets using LS-DYNA®

Jong S. Park
Ramakrishna Dospati
Ye-Chen Pan
General Motors
Amit Nair
Livermore Software Technology Corporation



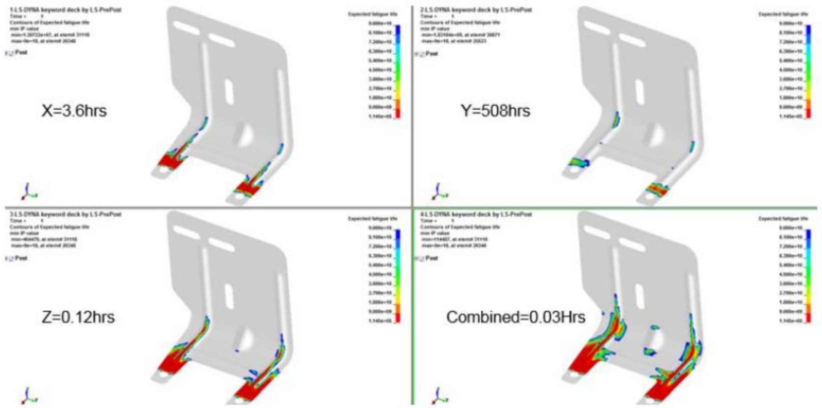
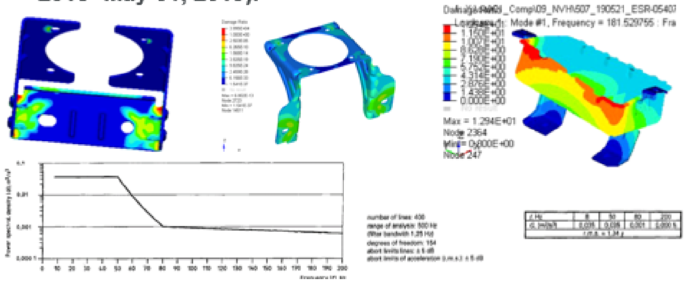


Figure 12: RVF Life Plot

- Prediction accuracy of the FE model is improved.
- 25 PAB bracket ESRs are counted, no DV failure occur (Jun 1, 2018- May 31, 2019).

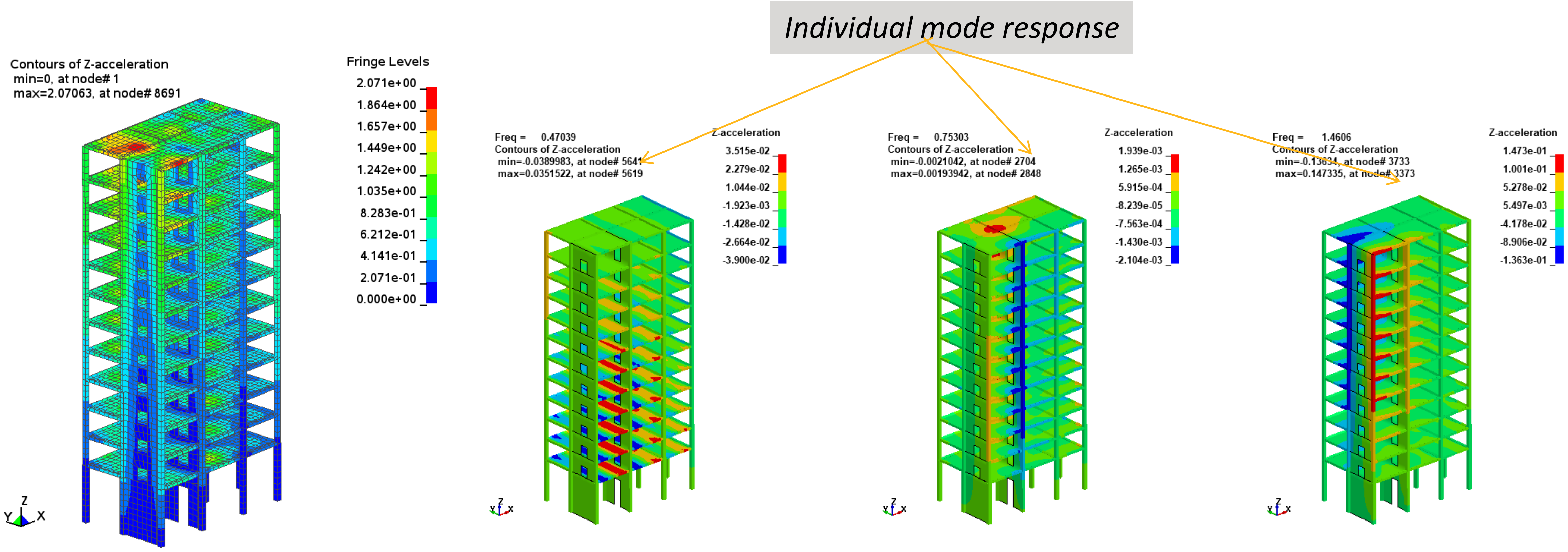


- **Benefit:**

	Time saving (h)	Cost saving (RMB)
With upper bracket (14)	14*72 = **1008 h**	**10w~50w**
Without upper bracket (11)	11*48 = **528 h**	**5w~25w**
Annual saved	1536 h / 24 = **64 day**	**15w~75w**

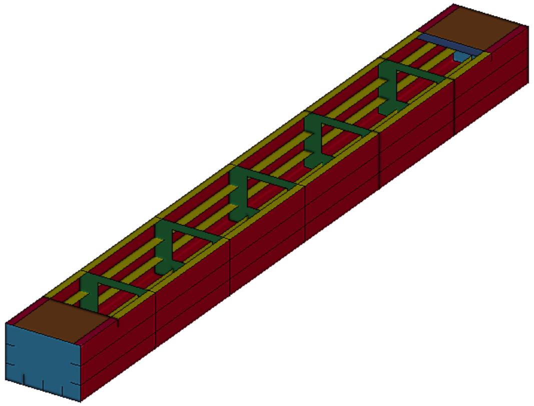
*FREQUENCY_DOMAIN_RESPONSE_SPECTRUM

With response spectrum analysis, peak values of response of buildings in an earthquake event can be computed and plotted, providing insight of structural safety in extreme conditions, to civil engineers.
Various modal combination methods are available: SRSS, CQC, NRC grouping, NRL-SUM, …
Multidirectional spectra can be considered using SRSS or 100-40-40 (ASCE 4-98) rules.



In fluid eigenvalue analysis

- *BOUNDARY_FLUIDM: A boundary integral approach to compute fluid added mass
- LOBPCG eigensolver to compute in-fluid eigenmodes: eigenmodes of structure immersed in incompressible, inviscid fluid.
- Vibration analysis using the "wet" modes.



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

Mode	Description	In-Air (Hz)		In-Fluid (Hz)	
		Experiment	LS-DYNA	Experiment	LS-DYNA
7	Torsion	16.1	15.1	14.9	14.8
8	Lateral bending	29.0	29.5	25.6	25.5
9	Vertical bending	38.3	37.1	29.5	28.5
10	Lateral bending	62.6	62.9	55.0	54.0
11	Vertical bending	94.2	91.0	68.5	65.8

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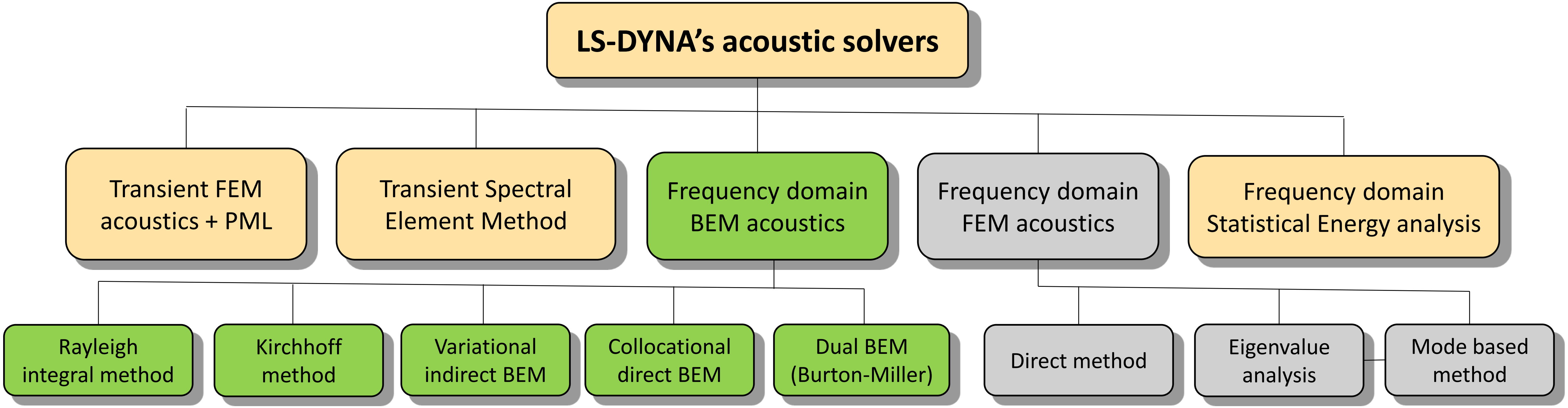
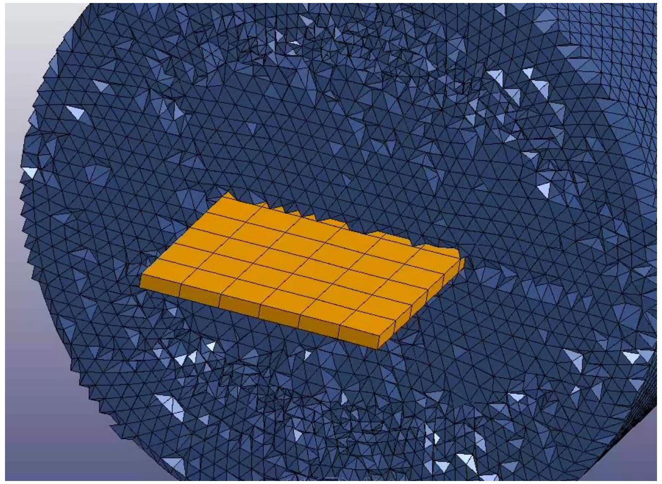
Acoustic solvers and their application

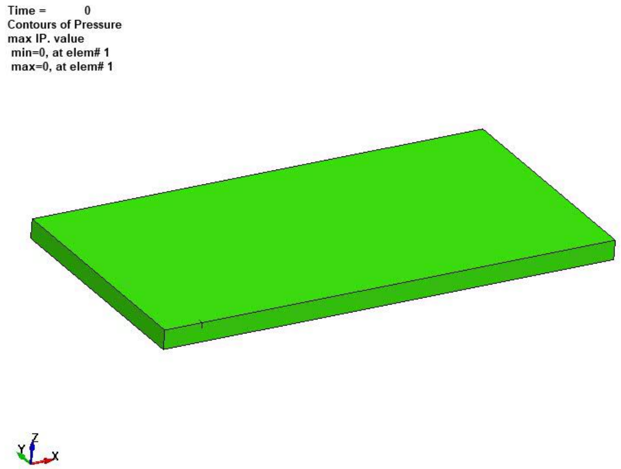
LS-DYNA's acoustic solver paradigm



Transient Acoustics by Finite Element Method

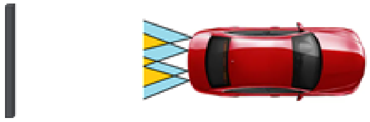
LS-DYNA provides transient acoustic analysis by using FEM and *MAT_ACOUSTIC. This material model applies to linear compressible and inviscid fluid, which undergoes small displacements and irrotational flow. This feature is effective for the transient analysis of acoustic wave propagation and structural interaction. It has applicability in marine engineering of ships and submarines subject to shock waves; earthquake engineering of dams with cavitation; noise modeling of impulsive loads in contained space and acoustic radiation from bodies in infinite/semi-infinite fluids.

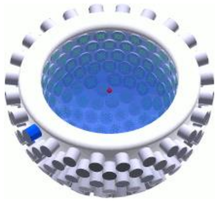




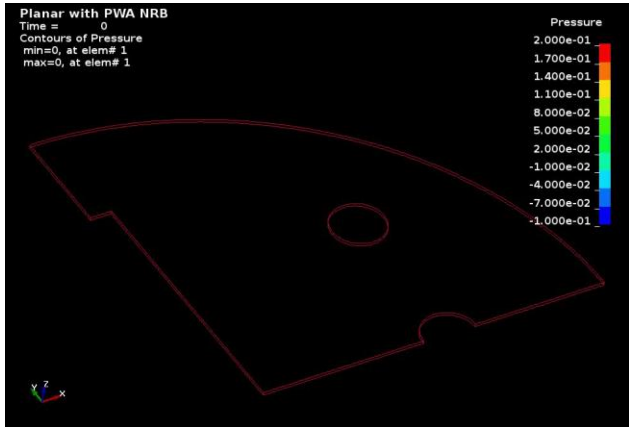
Transient Acoustics by Spectral Element Method

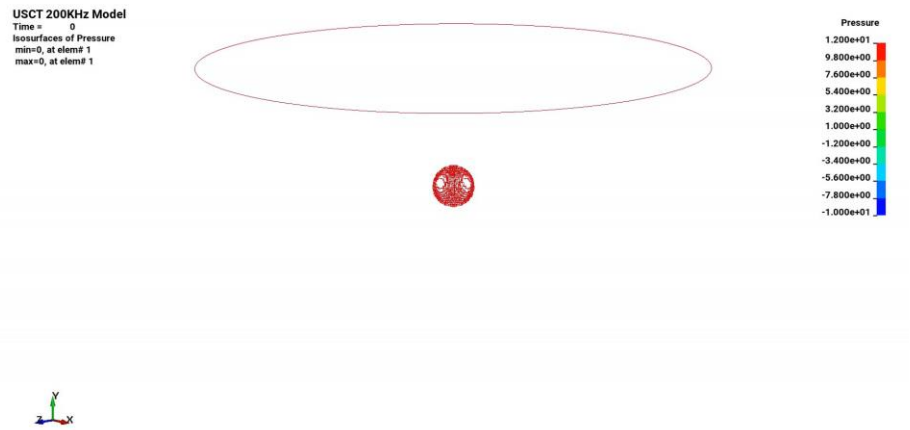
LS-DYNA provides also a spectral element method to model acoustic wave propagation as well as its absorption and reflection from boundaries. It is a sub-parametric FE. It is capable of high accuracy with manageable resource requirements, and so is well suited to high frequency and ultrasonic applications (e.g., ultrasonic sensors) where the wavelengths are often short relative to the dimensions of interest. It can find applications in autonomous driving / parking, and medical imaging simulation.





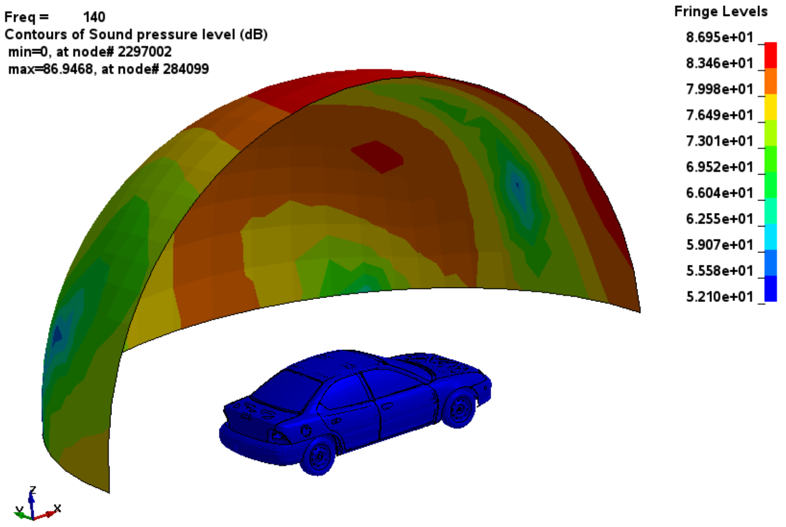
Ultrasound Computer Tomography

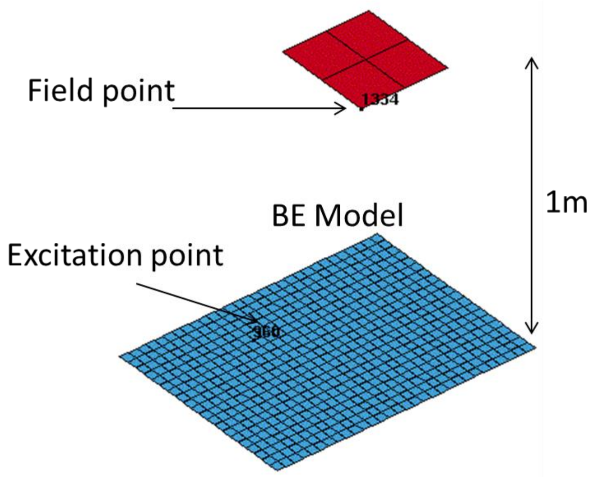


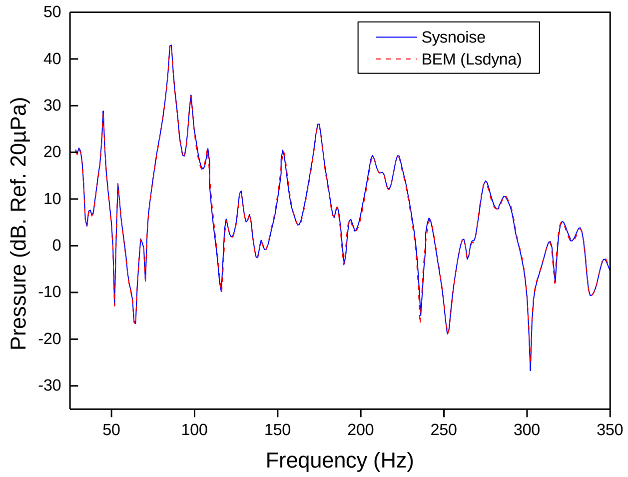


*FREQUENCY_DOMAIN_ACOUSTIC_BEM

LS-DYNA provides BEM for acoustic analysis. The radiated noise from a vibrating structure can be predicted. Variational indirect method, collocation method and simplified methods (Rayleigh method, Kirchhoff method) are provided. A fast solver based on domain decomposition, and the low rank approximation of the matrices is implemented. Combining with transient or frequency domain vibration response solver in LS-DYNA, this feature provides seamless solution for vibro-acoustic problems. Acoustic wave reflection from rigid surfaces can be considered. Incident waves are included. “Frequency” weighted SPL is also available.

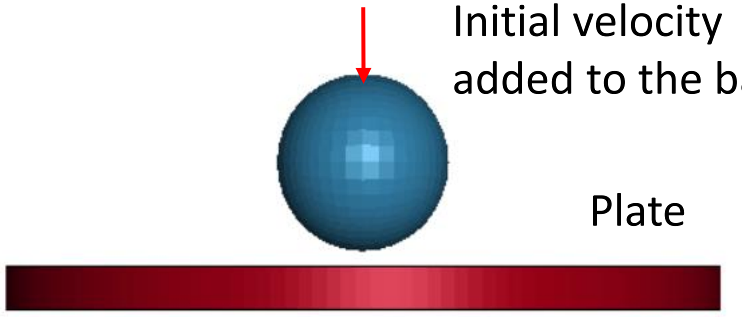






Sysnoise result provided by ARUP

User can actually “hear” the sound by converting the acoustic pressure curve to an audio file using LS-PrePost (Chengju Zhang, Wenhui Yu, Philip Ho).



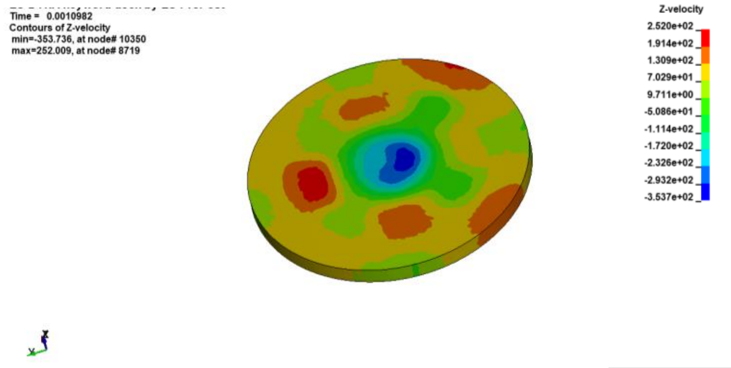
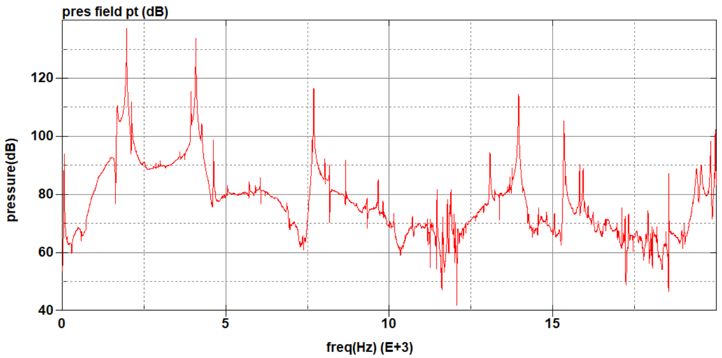


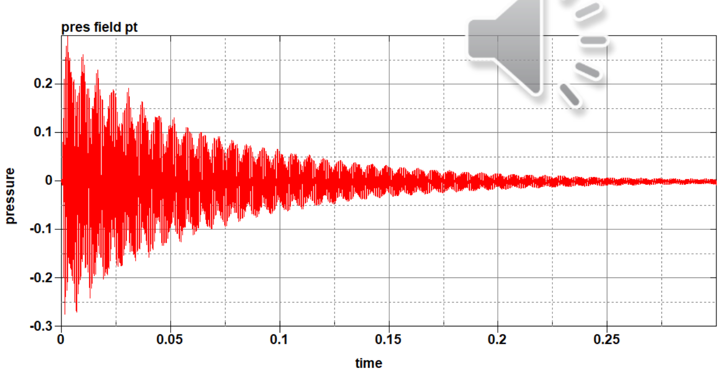
Plate transient response

Material: **Titanium alloy**

Density: 4.167E-04 lbf-s²/in⁴,

Young’s modulus: 1.653E+07 Psi

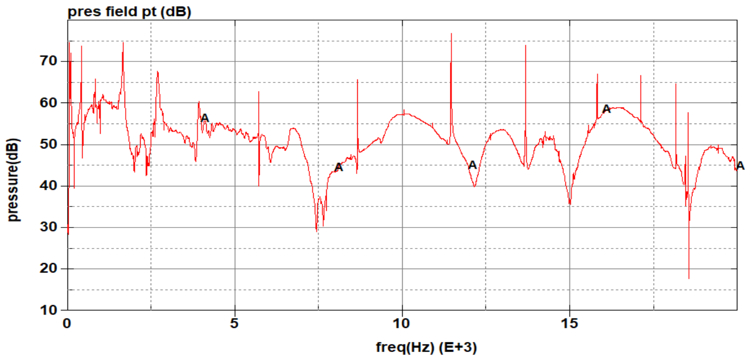


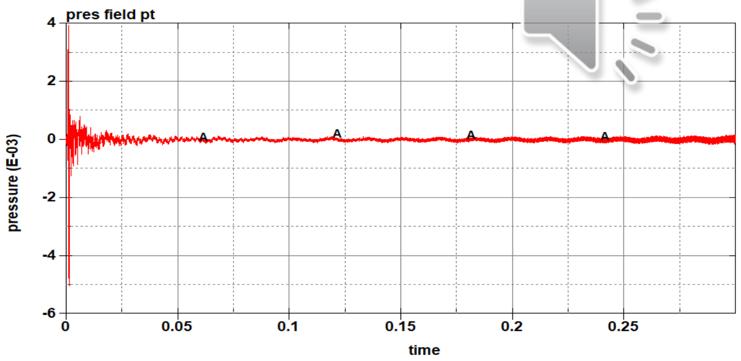


Material**: Pine wood**

*MAT_WOOD_PINE

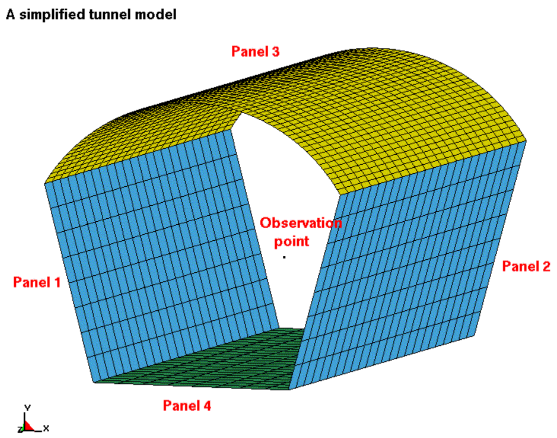
Density: 6.730E-04 lbf-s²/in⁴

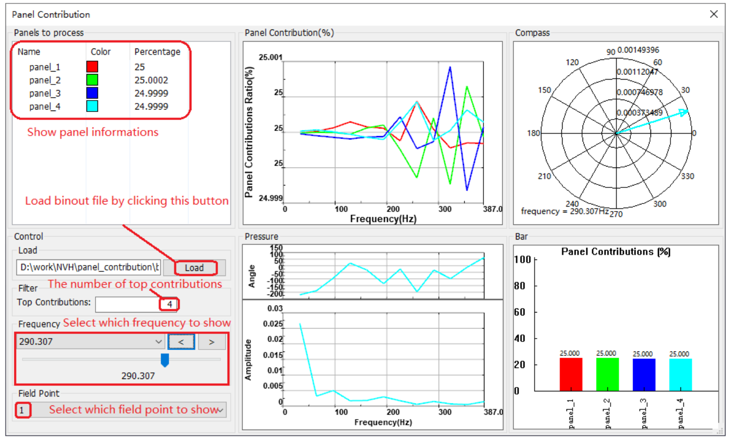




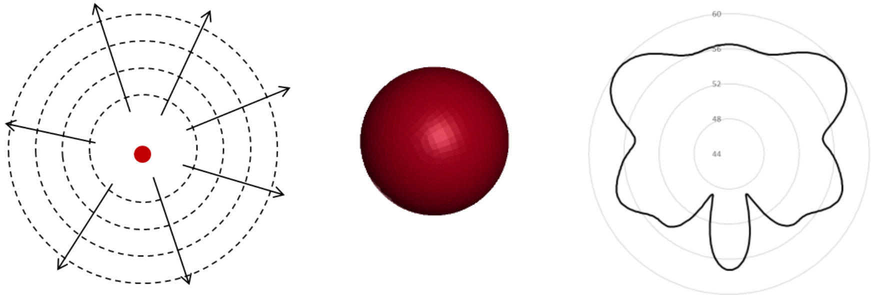
More output from BEM acoustic analysis

- Panel contribution analysis
- Element contribution plot (d3acc)
- Acoustic directivity plot
- Acoustic transfer vectors (d3atv)
- Acoustic fringe plot (d3acp)

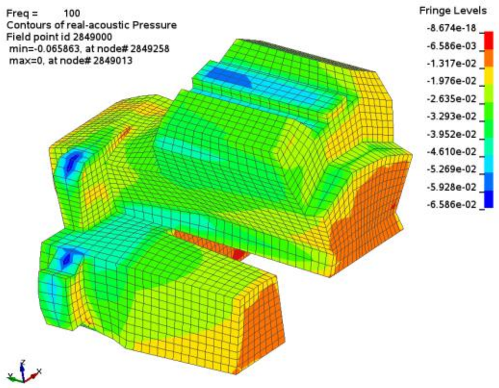




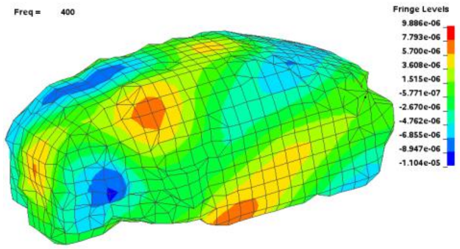
Panel contribution analysis



Acoustic scattering of a monopole incident wave on a rigid sphere



D3atv: a simplified engine



D3acs: real part of surface pressure

Application cases

9th European LS-DYNA Conference 2013

Transmission loss simulation of acoustic elements in LS-DYNA®

Marko Krebelj

Akrapovič d.d.

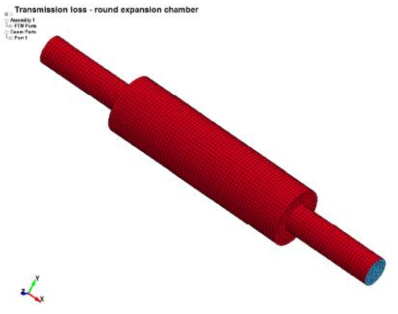
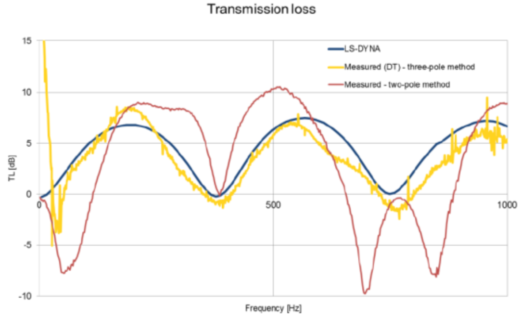


Fig. 4: Meshed model of round expansion chamber.



15th International LS-DYNA® Users Conference *NVH*

Verification of Sound Absorption Characteristics Constituted Porous Structure

Toru Yoshimachi[1], Ryo Ishii[1], Kuniharu Ushijima[2], Naoki Masuda[2], Takao Yamaguchi[3], Yun Huang[4], Zhe Cui[4]

[1] *JSOL Corporation, Japan*

[2] *Tokyo University of Science, Japan*

[3] *Gunma University, Japan*

[4] *Livermore Software Technology Corporation, USA*

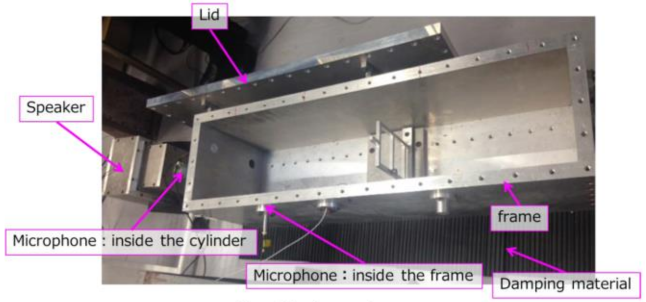


Figure 1 Experiment equipment

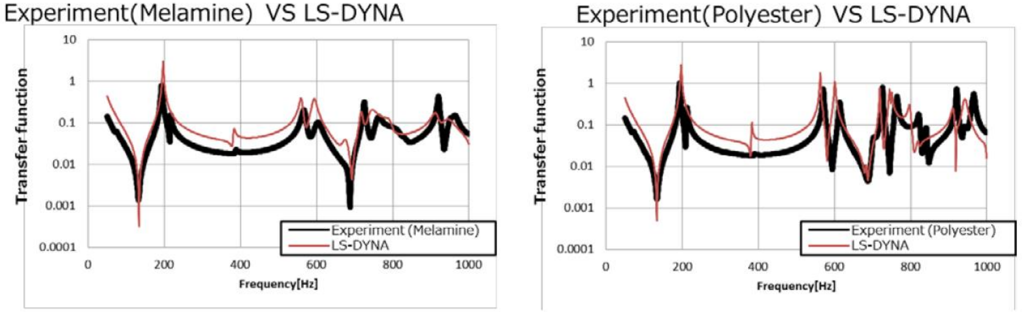
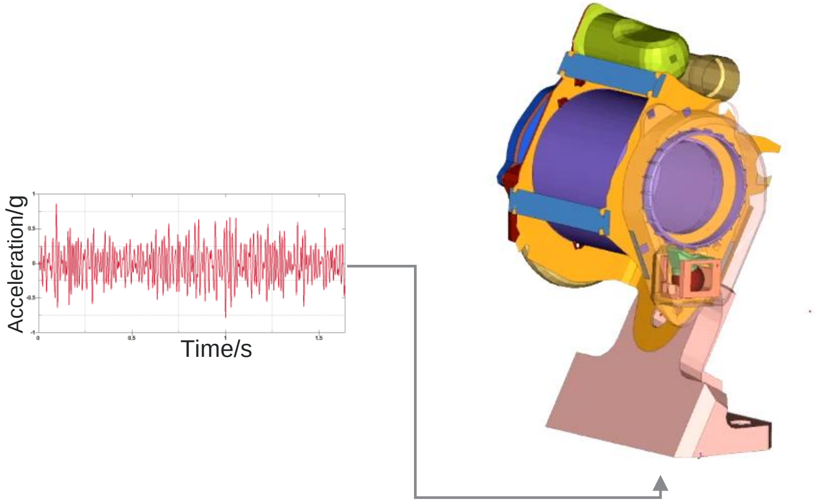


Figure 11 : Sound absorption is attached to the jig

Application cases

Autoliv



Application of LS-DYNA® to NVH Solutions in the Automotive Industry

Prasanna S. Kondapalli, Tyler Jankowiak
BASF Corp., Wyandotte, MI, U.S.A

Yun Huang
LSTC Corp. Livermore, CA, USA

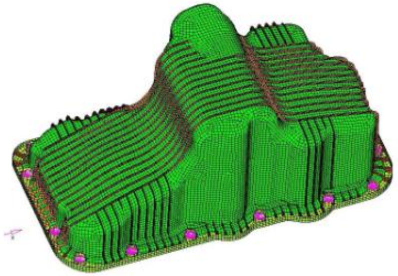


Figure 1 Plastic Oil Pan made of Ultramid® A3WG7 (Glass Reinforced Polyamide 66)

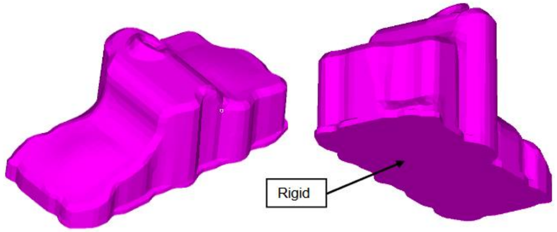


Figure 9 Boundary element model of oil pan

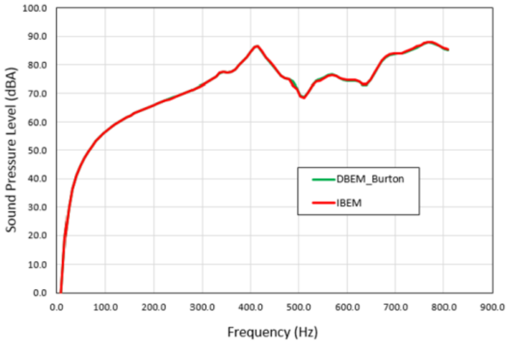
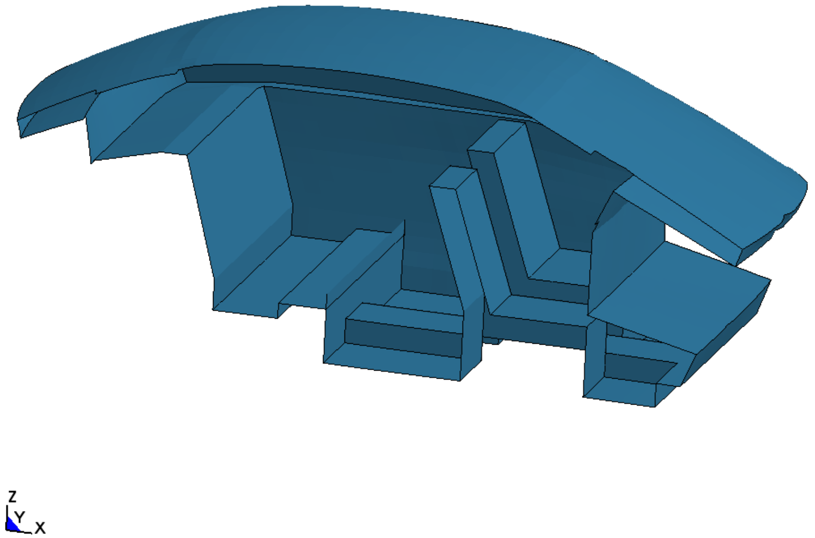


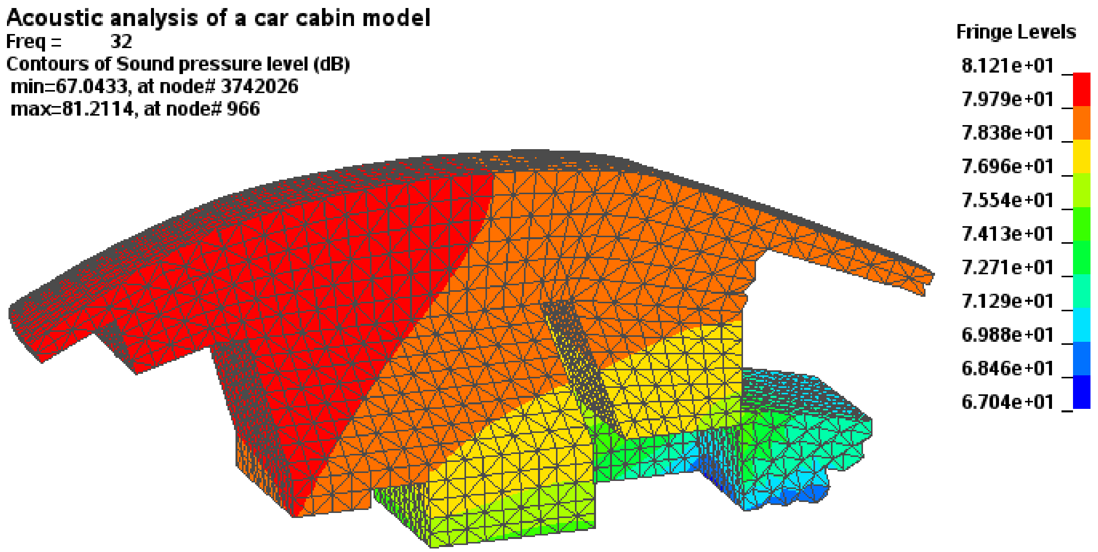
Figure 10 Sound Pressure Level (dBA) at 1/2 meter above Oil Pan

Ansys

*FREQUENCY_DOMAIN_ACOUSTIC_FEM

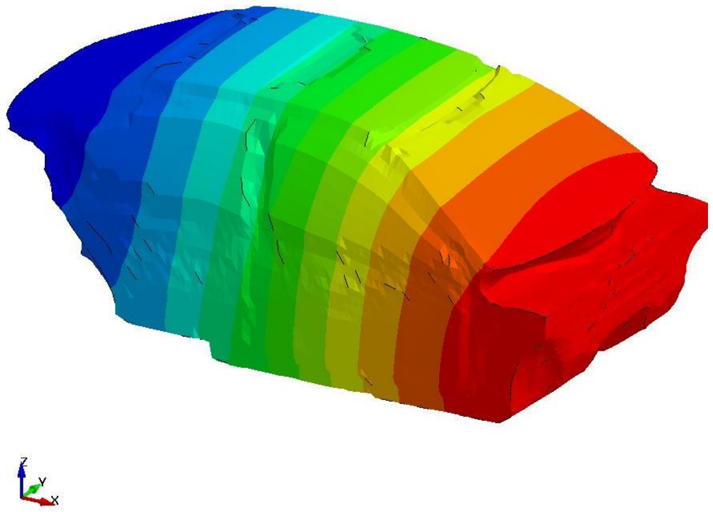


With FEM Acoustic solver in LS-DYNA, user can compute the noise distribution in a car cabin model, for each excitation frequency. The results are given by D3ACS, accessible to LS-PREPOST.

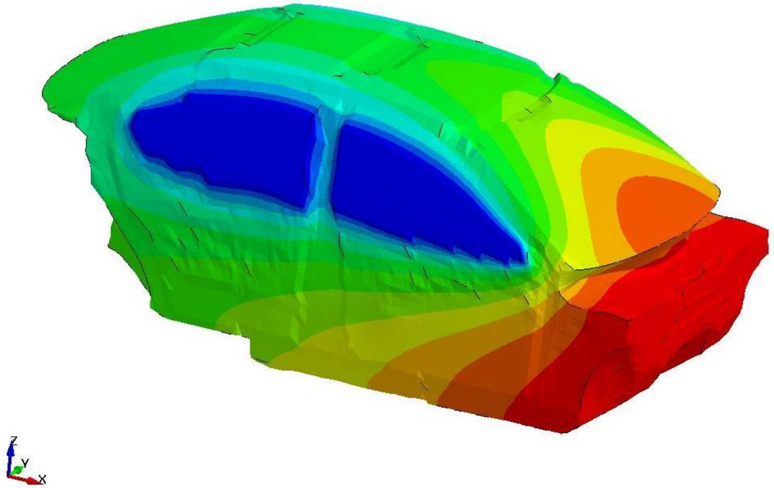


*FREQUENCY_DOMAIN_ACOUSTIC_FEM_EIGENVALUE

LS-DYNA can run acoustic eigenvalue analysis, to compute eigenfrequencies and eigenvectors for an acoustic domain. The eigenfrequencies are saved in ascii database EIGOUT_AC. The eigenvector results are saved in binary plot database D3EIGV_AC, accessible to LS-PREPOST.



Acoustic eigenvector of a cabin when windows are closed

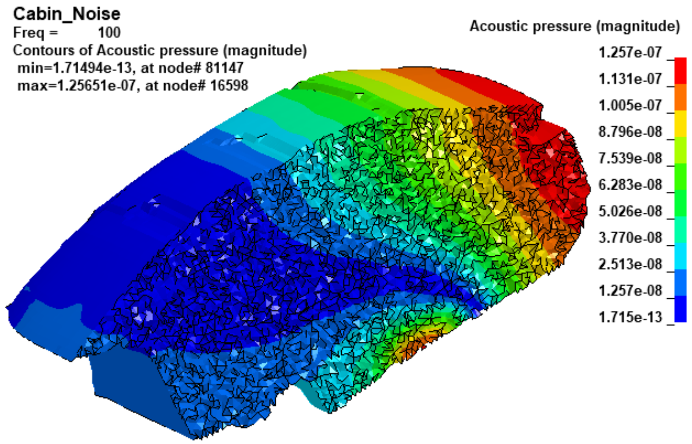


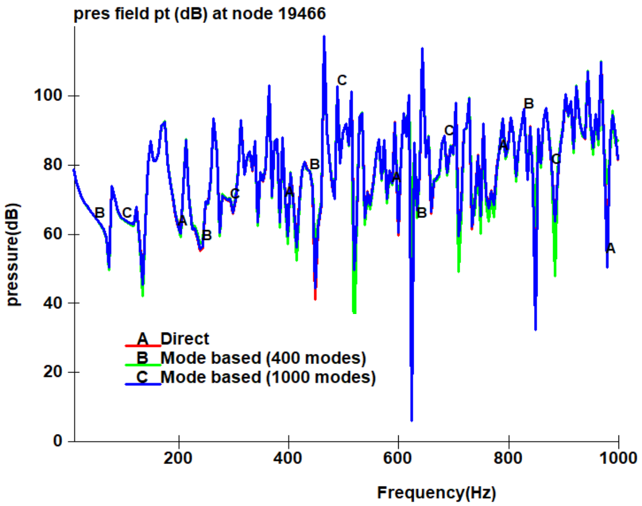
Acoustic eigenvector of a cabin when windows are open

Ansys

*FREQUENCY_DOMAIN_ACOUSTIC_FEM_MODAL

LS-DYNA can run acoustic analysis using modal superposition method. The unknowns are just the modal coordinates for the acoustic eigenvectors. It can be much cheaper than the full method which is based on the physical unknown variables. As the acoustic eigenmodes can be reused, this method is also very useful for the case with multiple loading cases.





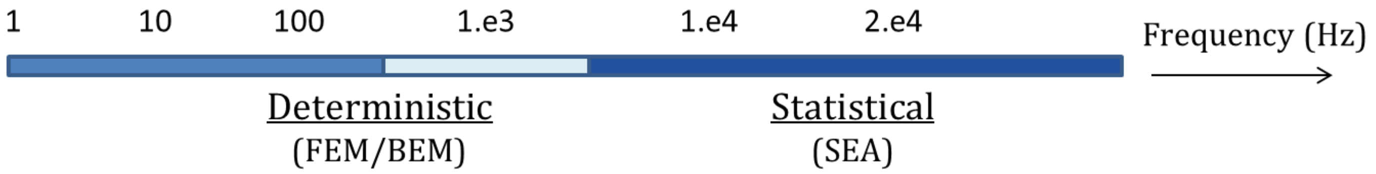
CPU cost (sec) for different methods

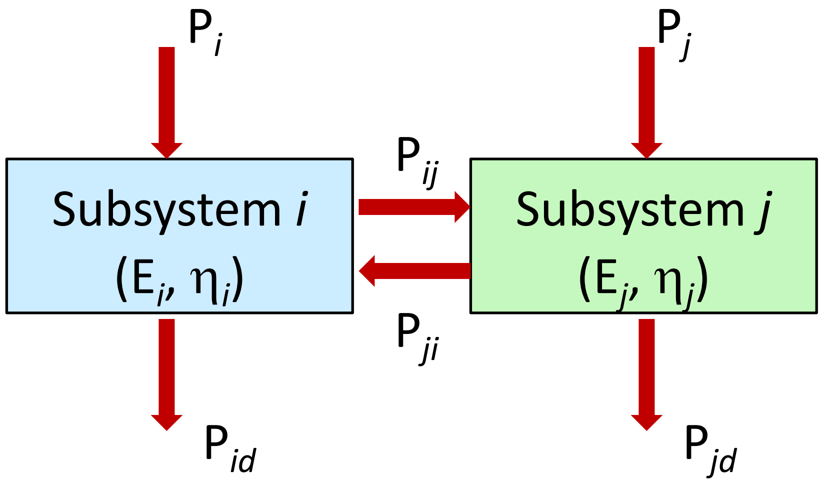
Direct	Modal	
	400 modes	1000 modes
2283	308 = 270[1]+38[2]	597 = 527[1]+70[2]

1. Acoustic eigenvalue analysis
2. Acoustic pressure computation

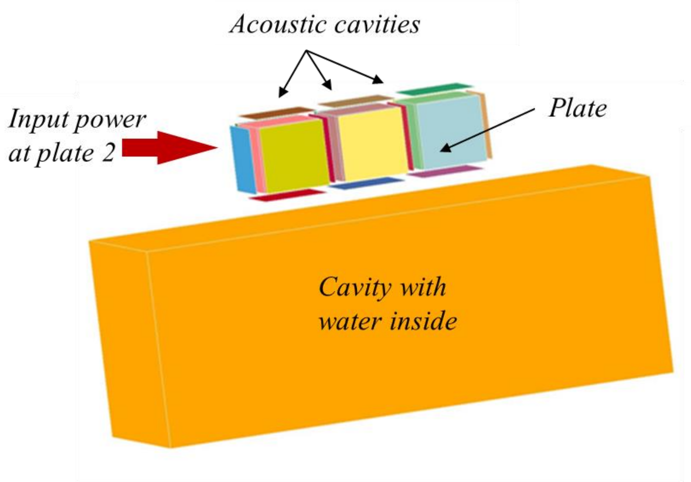
*FREQUENCY_DOMAIN_SEA

SEA is a statistical method for studying vibration and acoustics in high frequency range, without using elements or mesh. In SEA a system is represented in terms of a number of coupled subsystems and a set of linear equations are derived that describe the input, storage, transmission and dissipation of energy within each subsystem.





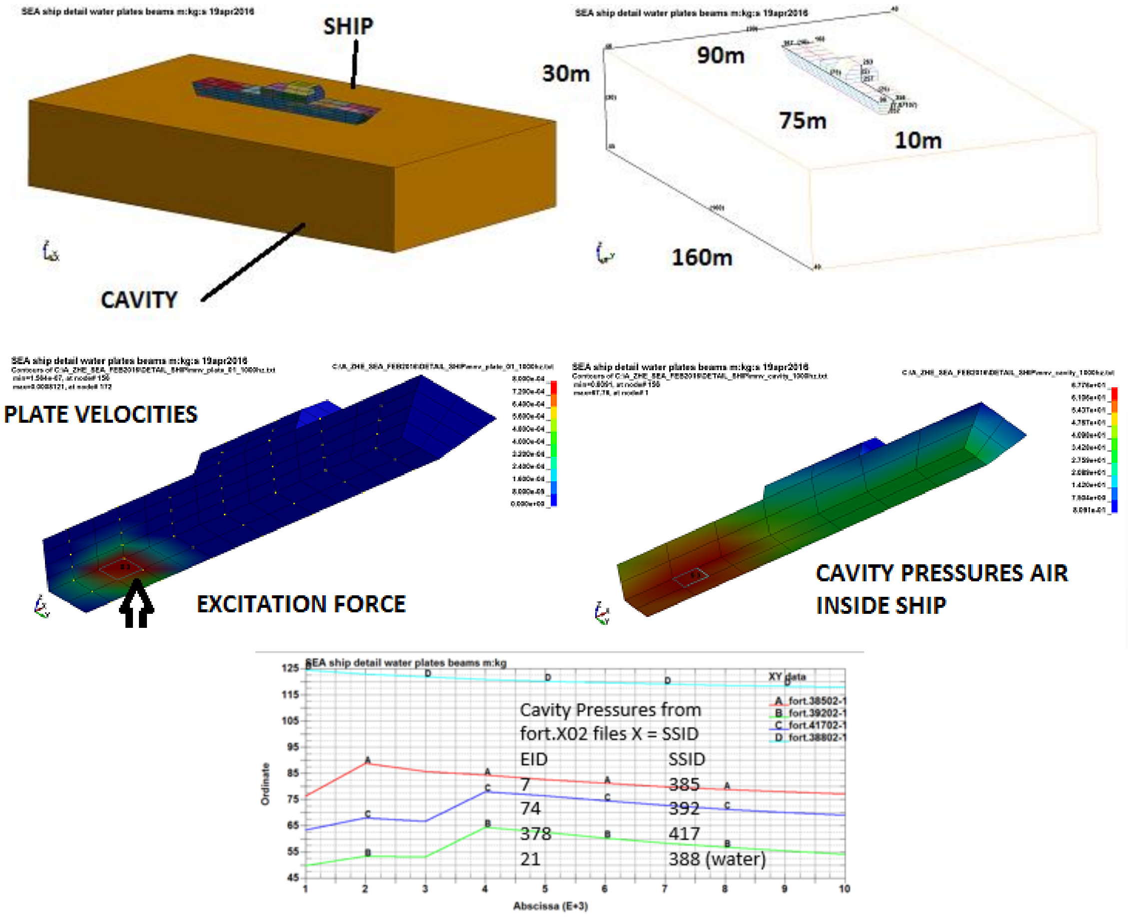
SEA model of 2 subsystems



Application cases

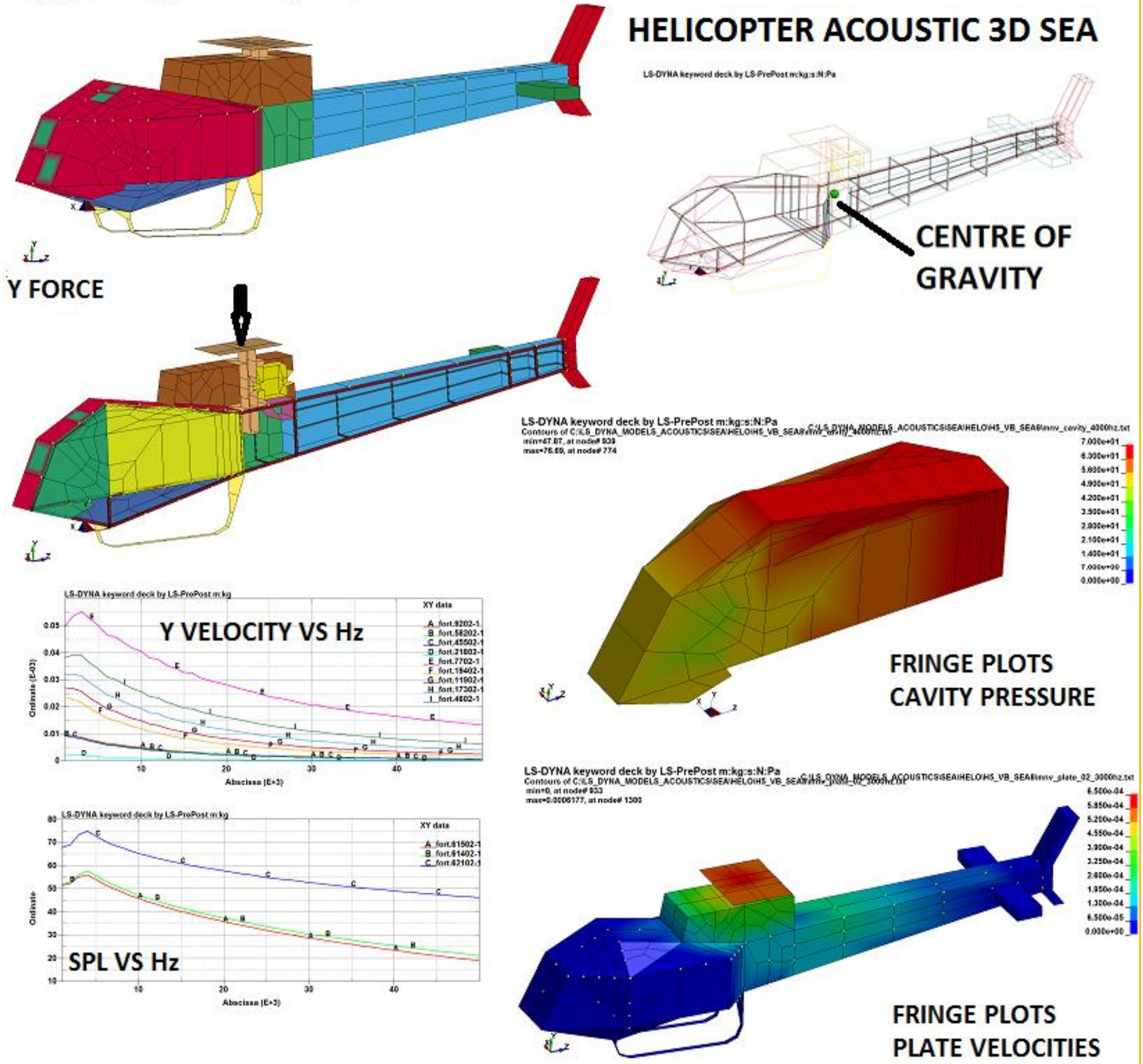
DETAIL SHIP 3D SEA

Cavity (air and water), Plate and Beams modelled as subsystems.
Bending Force applied at plate EID:8. Frequency range 1kHz to 10kHz
Statisical Energy Analysis solver used to calculate pressure in a cavity and velocity of a plate.



HELICOPTER ACOUSTIC 3D SEA2

Air modelled with solids, helicopter modelled with shells and beams.
Y Force applied at top of rotor, frequency range 1kHz to 50kHz.
Fringe plots cavity pressure and plate velocities



Summary

Summary

- A series of NVH solvers have been developed in LS-DYNA
  - Focused on application in automotive industry, where LS-DYNA has been widely used.
  - Allow users to run NVH analysis with minor changes to their existing LS-DYNA models (crash, etc.)
  - “One button” Crash model to NVH model conversion is on the way
  - Aiming at multi-disciplinary design optimization for vehicles, with other modules in LS-DYNA.
  - Seamless coupling / integration with other solvers in LS-DYNA (e.g. metal forming)
- Well supported by OASYS (PRIMER/D3PLOT 20.0) and LS-PrePost for Pre and Post-processing
- Is being integrated to Ansys Mechanical environment
- Tested and validated by many users (still, this is an on-going effort, and we need your help ☺)
- Training (in UK locally by Arup team), tutorials and samples are available
- More features to be added (adaptive remeshing for boundary elements, nonlinear acoustics, DPF workflow to connect LS-DYNA with other Ansys products, etc.)
- Looking forward to feedback and suggestions from UK customers ☺

Ansys