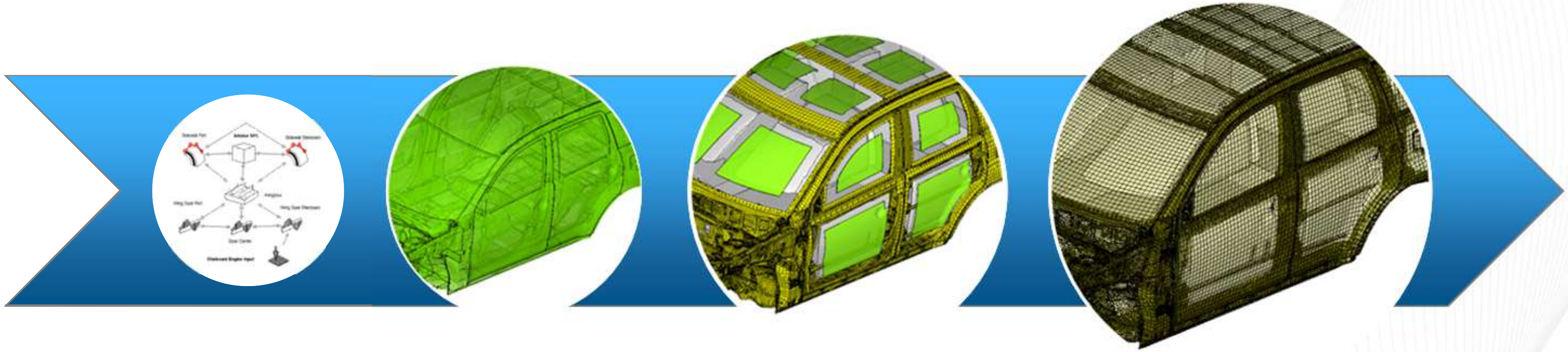
Coupling CFD,FEM,BEM,PEM and SEA to Improve Acoustics in Vehicles

10 years after first implementation



Denis Blanchet

January22nd,2015

Symposium on International Automotive Technology 2015

Towards Safer, Cleaner & Quieter World...

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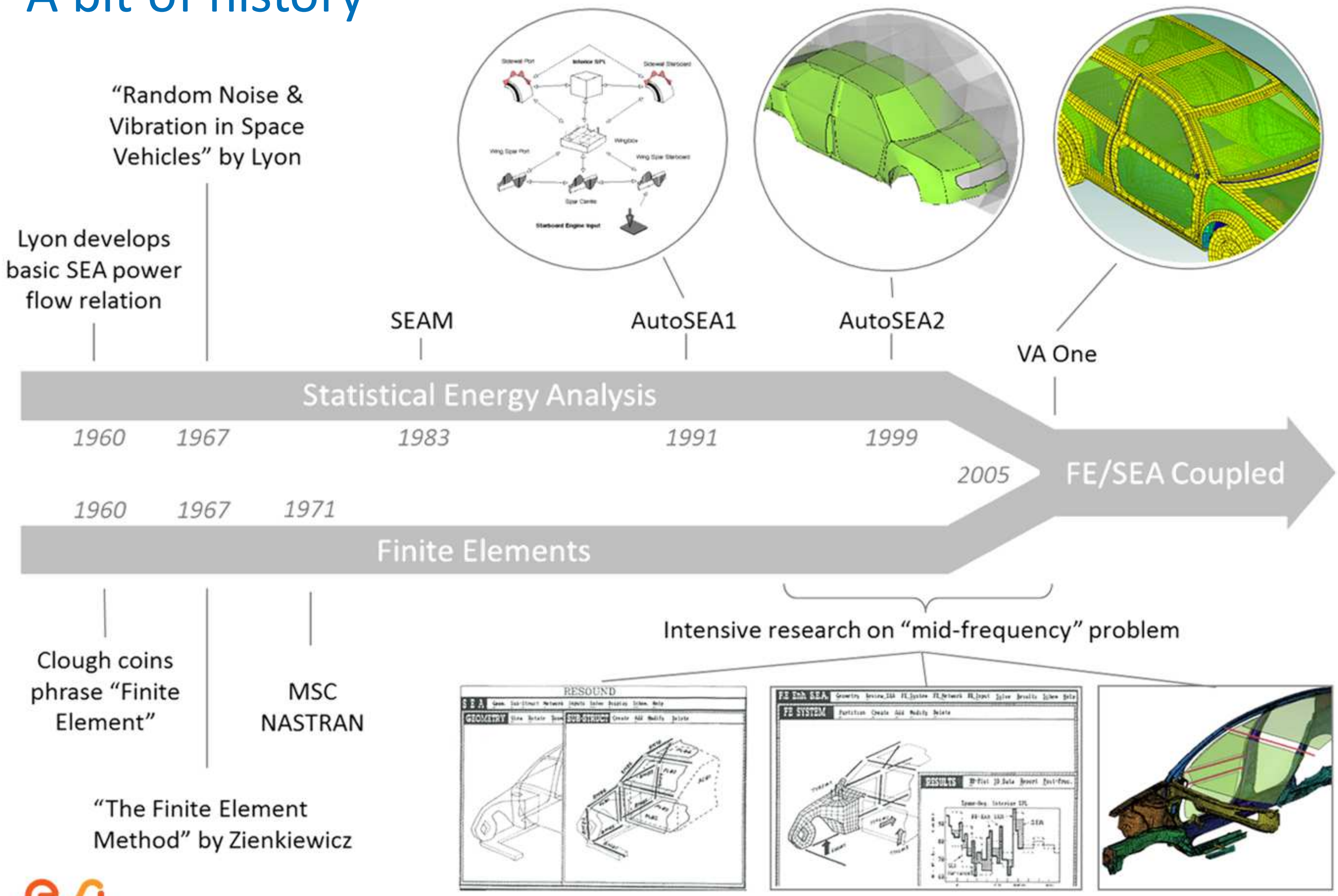
SAEINDIA The Engineering Society For Advancing Mobility Land Sea Air and Space

NATRiP Driving India Into The Future

A bit of history

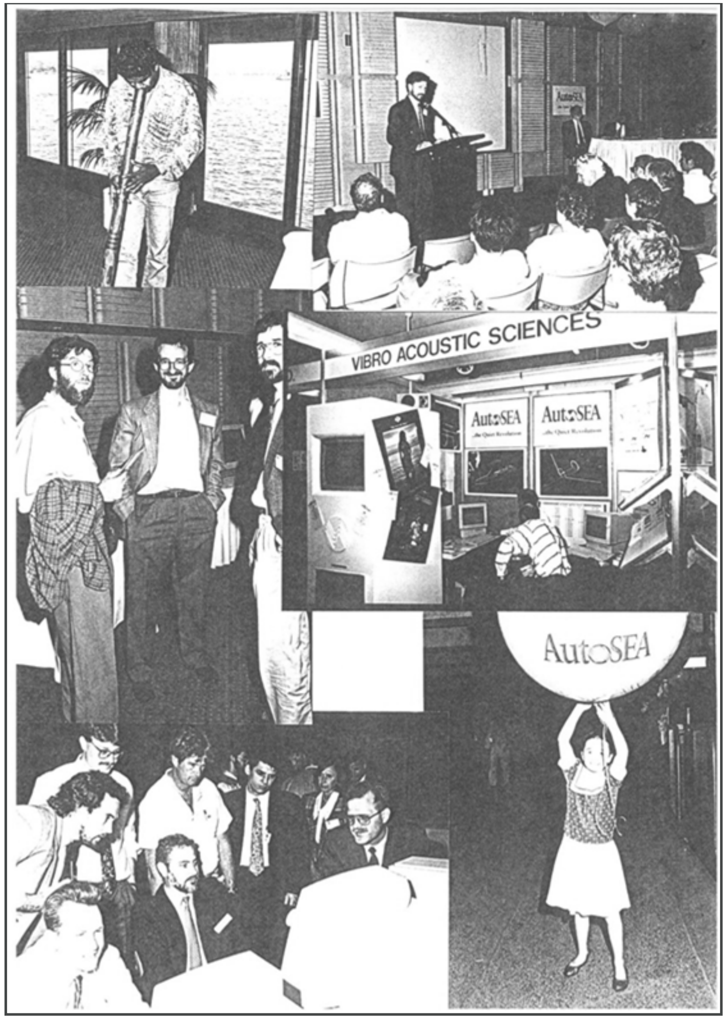


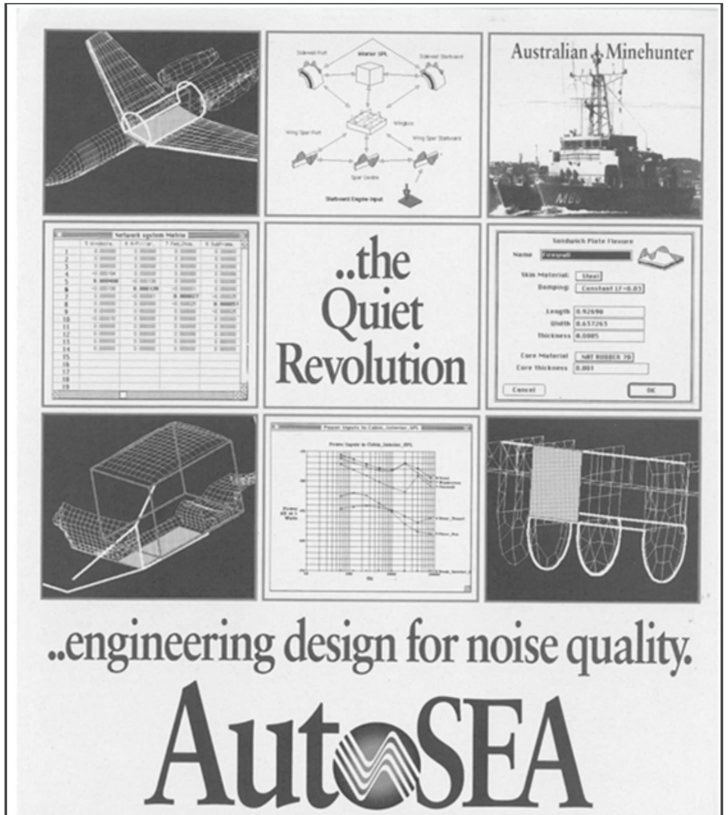
AutoSEA 1 product launch

Internoise 1991, Sydney Australia

AutoSEA 1 product launch

Internoise 1991, Sydney Australia





AutoSEA represents the evolution of structural acoustic design from the noise and vibration test lab, to the computer-aided engineering (CAE) design world. It provides the first fully graphical, object-oriented implementation of the method of Statistical Energy Analysis.

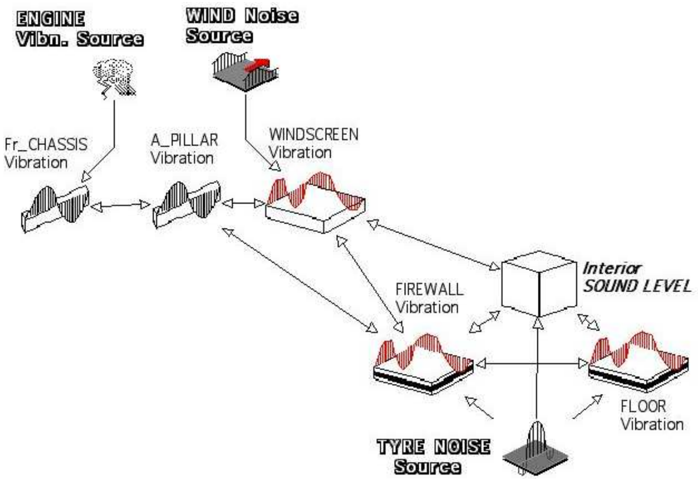
AutoSEA provides "Systems Analysis" tools for optimising the acoustic and vibrational quality of almost any product, from consumer whitegoods to architectural environments. It is especially popular with automotive, aerospace and ship building companies concerned with noise paths through complex structures.

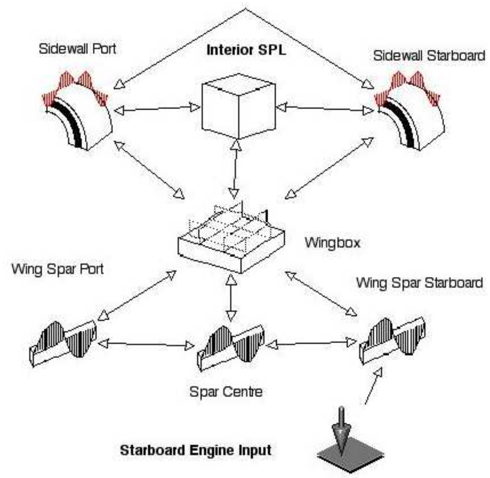
Dr. Ken Hews-Taylor, Manager of Acoustics & Mechanics, C.S.I.R.O. Division of Applied Physics said; *"AutoSEA enables you to predict and analyse sound and vibration levels in a complex structure, given a number of sources of energy input".*

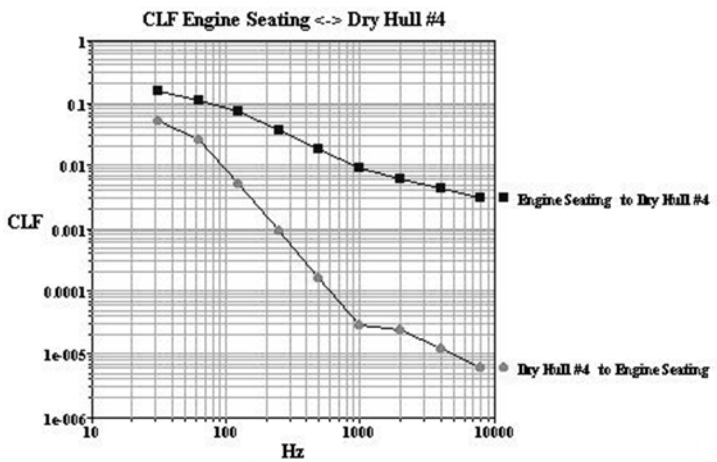
Senior Staff Engineer with Ford Motor Company's Alpha Group in the United States, Mr Paul Geck said; *"The SEA method has the potential to improve our structural-acoustic design and to save weight normally added by costly interior trim. Energy methods such as AutoSEA are also expected to reduce our product development time".*

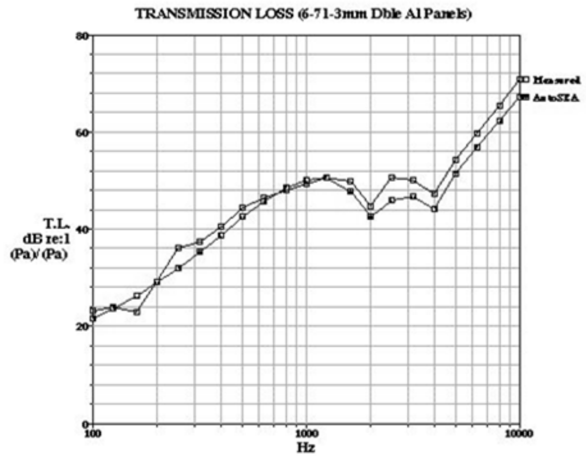
AutoSEA 1 product launch

Internoise 1991, Sydney Australia







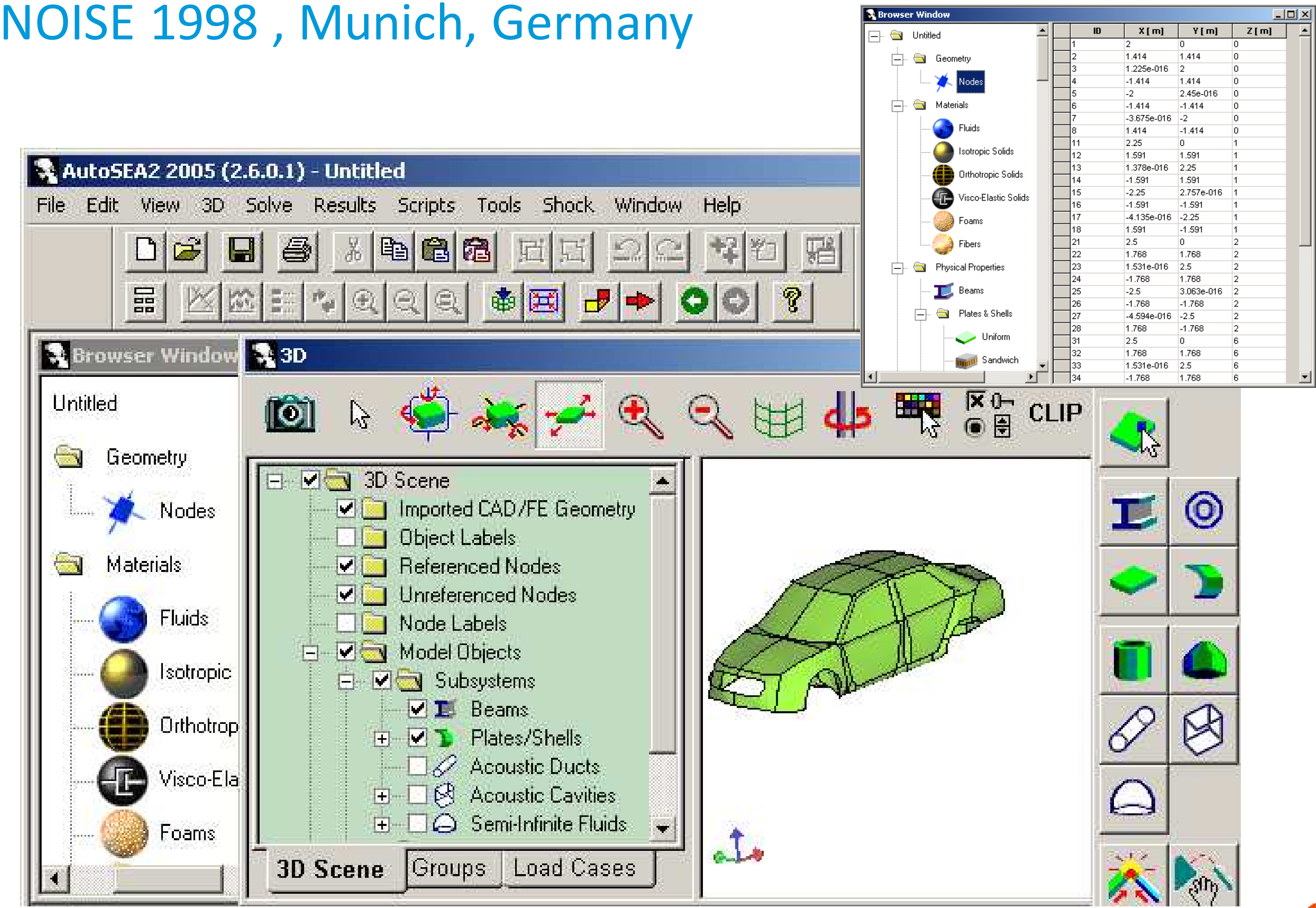


AutoSEA 2 product launch

EURONOISE 1998 , Munich, Germany

AutoSEA 2 product launch

EURONOISE 1998 , Munich, Germany



VA One product launch

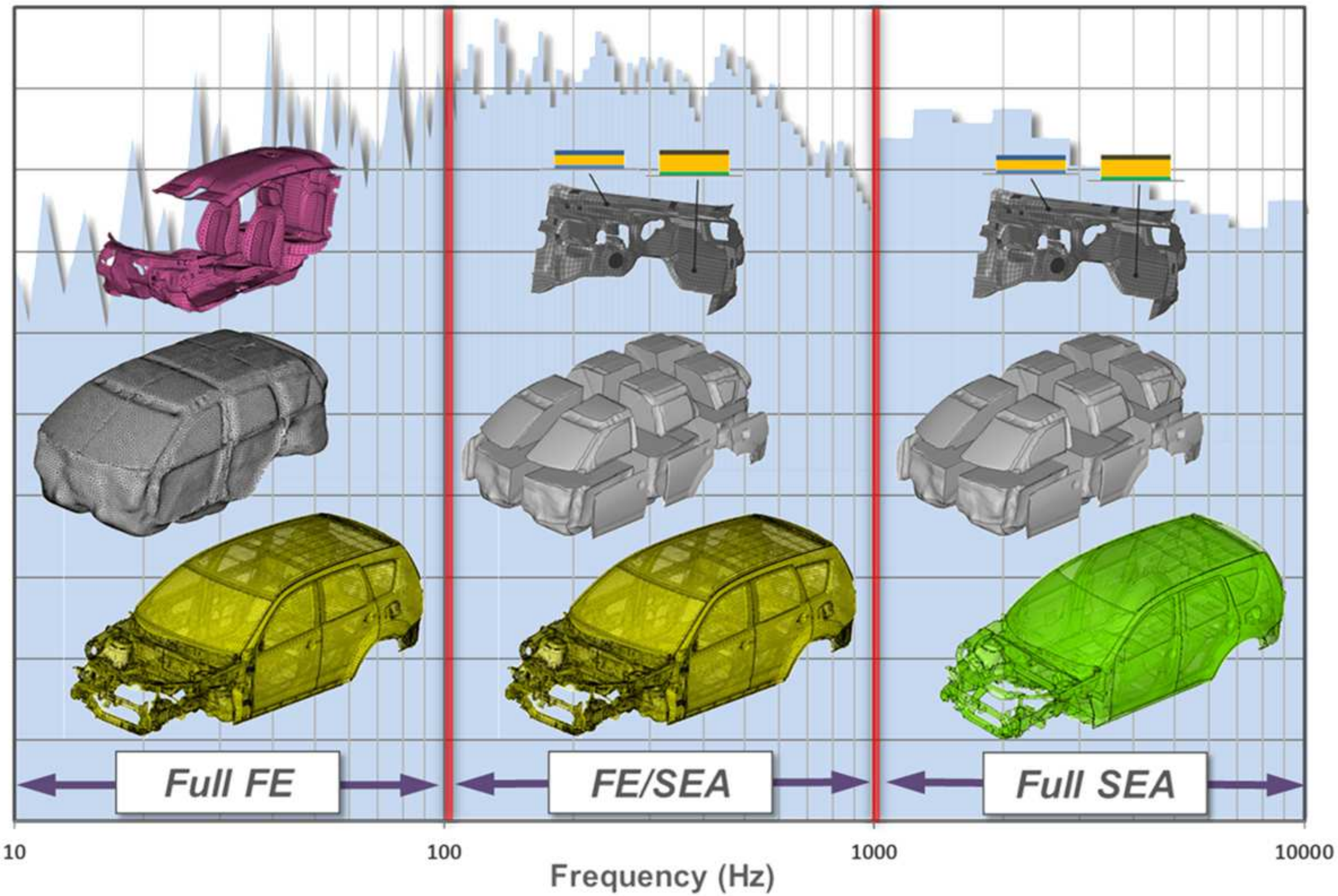
Internoise 2005 , Rio de Janairo, Brasil

VA One product launch

Internoise 2005 , Rio de Janairo, Brasil

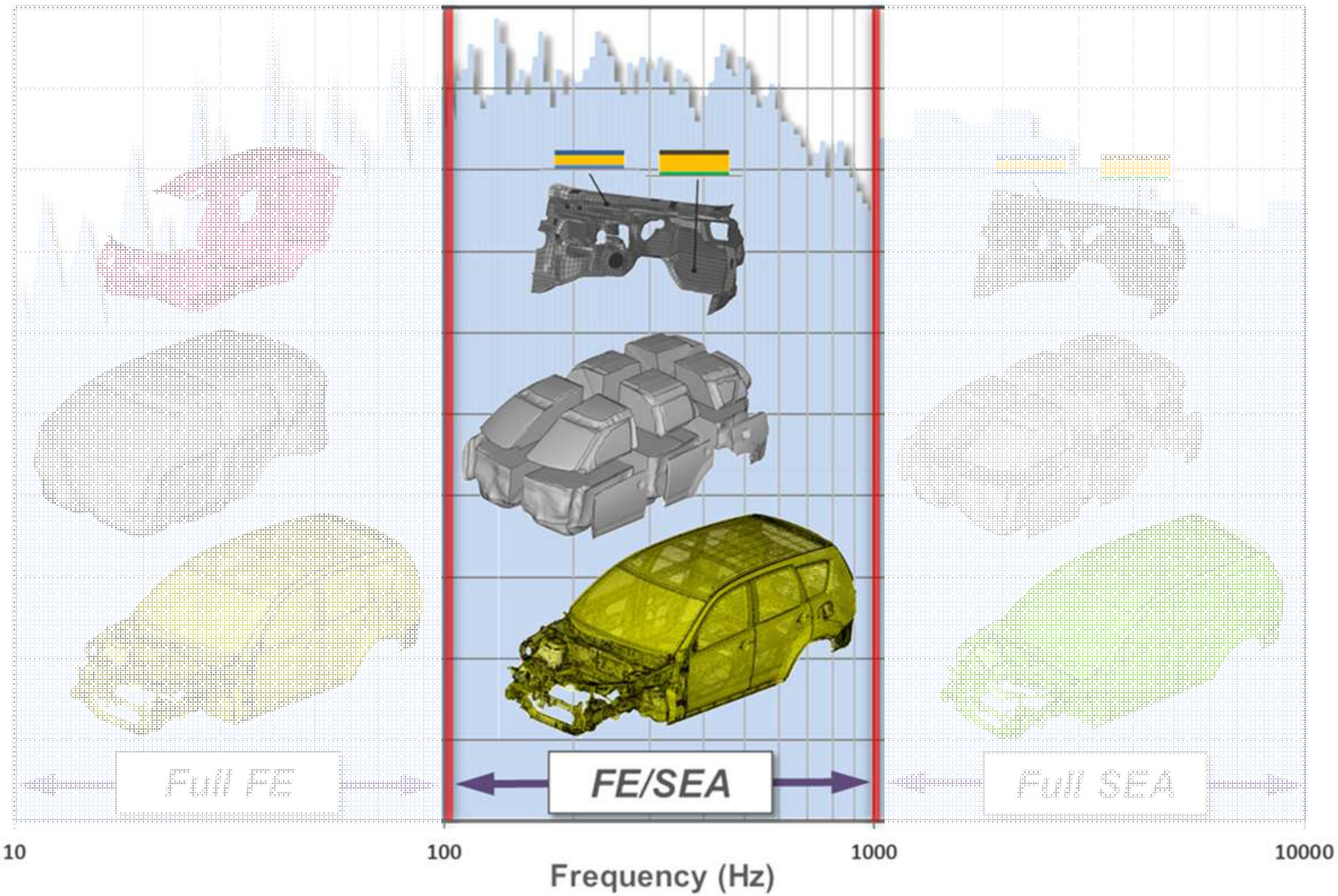
The right combination of methods…

…for the right frequency domain

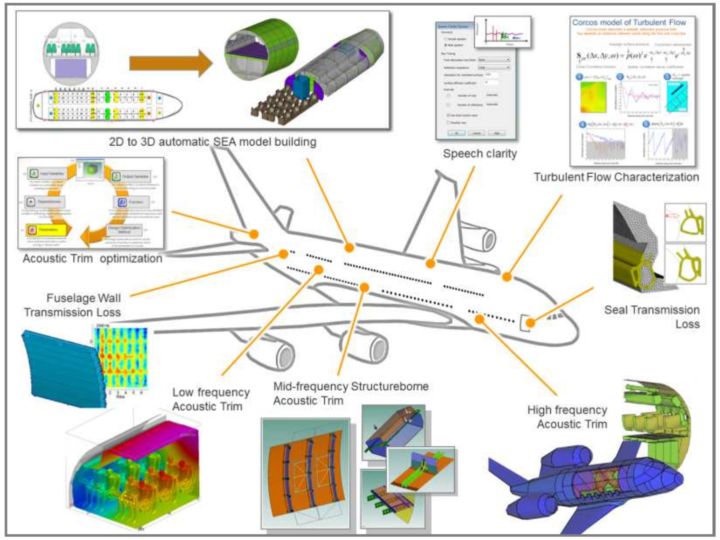


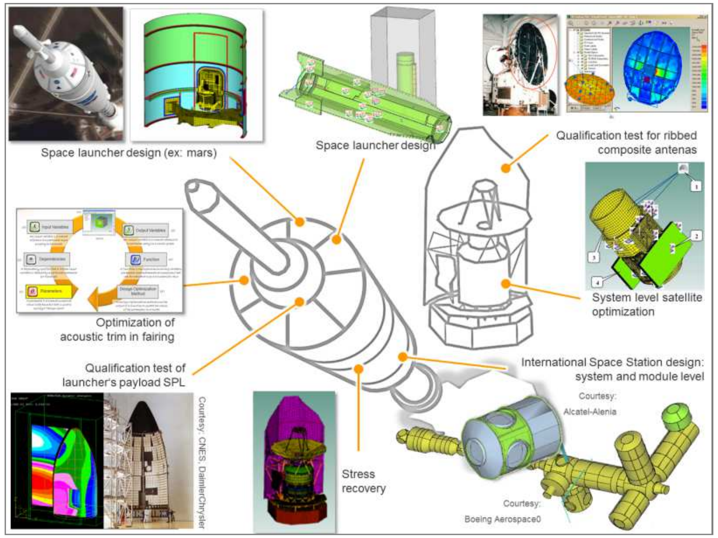
The right combination of methods…

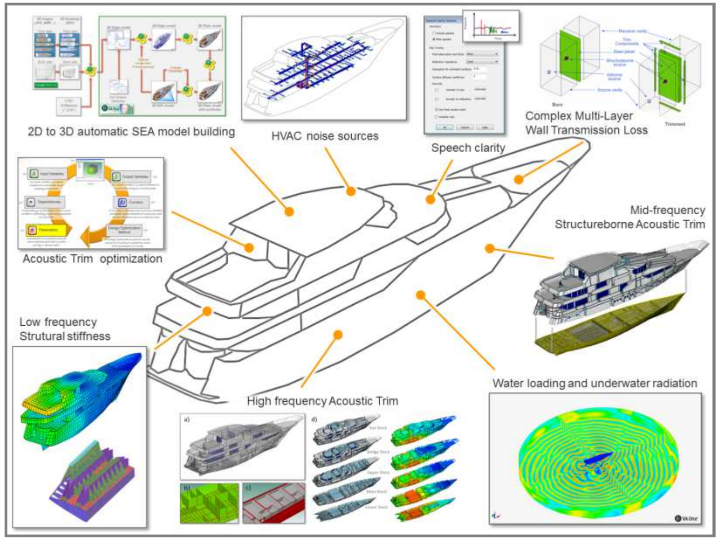
…for the right frequency domain

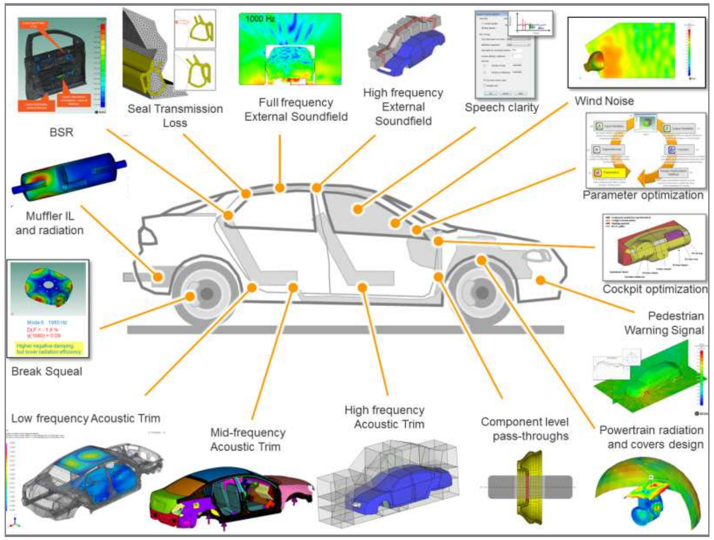


Wide range of application worldwide





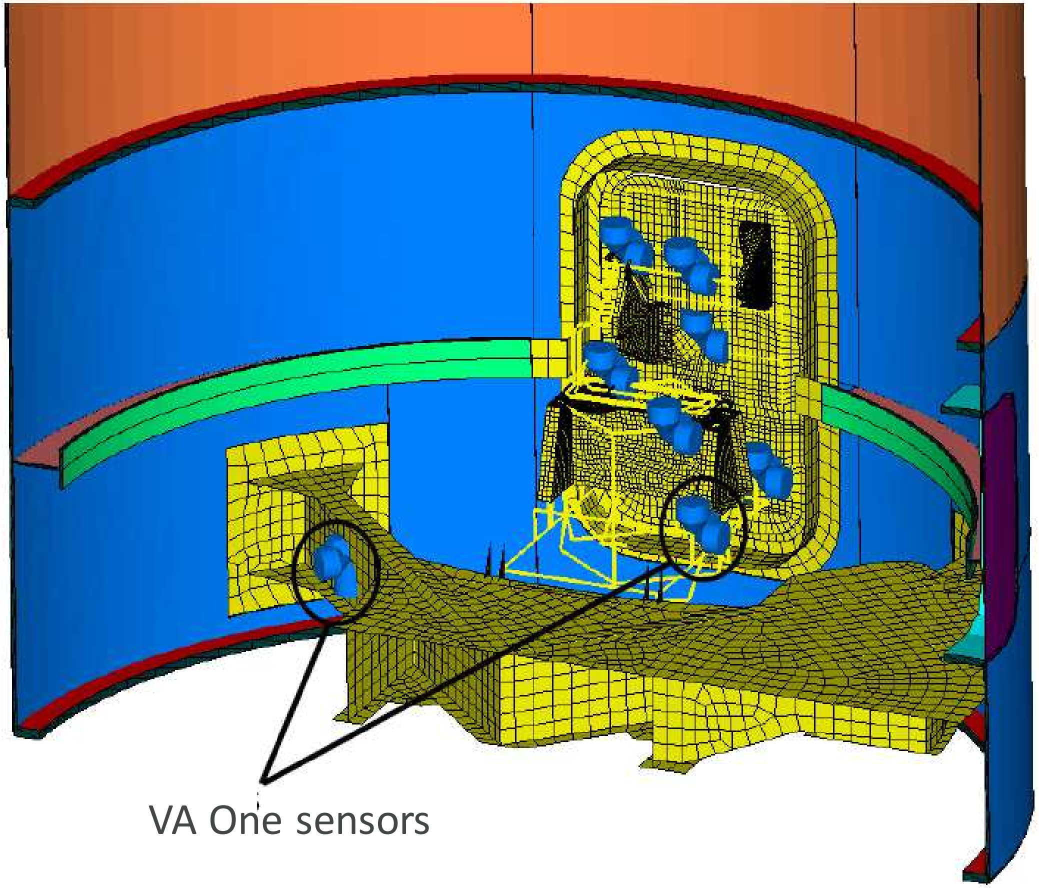




Space launcher design

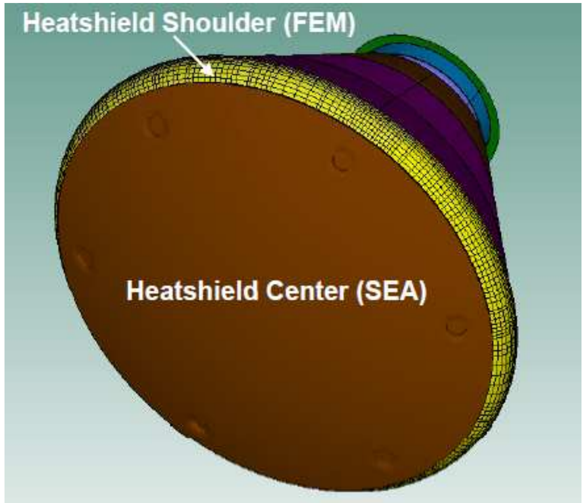
ATA Engineering

- 'Sensors' placed to recover local nodal responses of critical components
- Hybrid Analysis run from 20-2000 Hz in 5-Hz bands
  - Shorter bandwidth required to recover peaks in the FEM subsystem responses



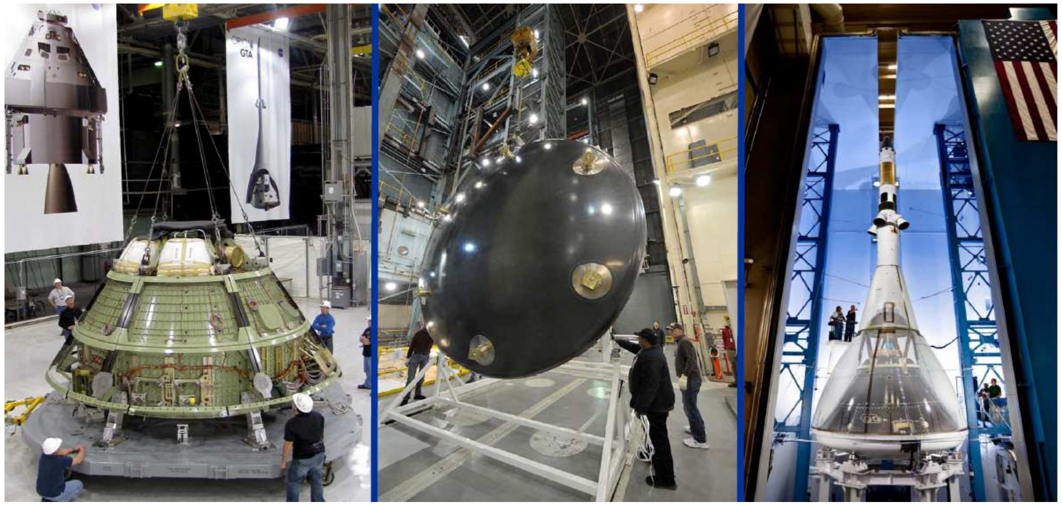
Space launcher design

Lockheed Martin



Orion GTA Integration

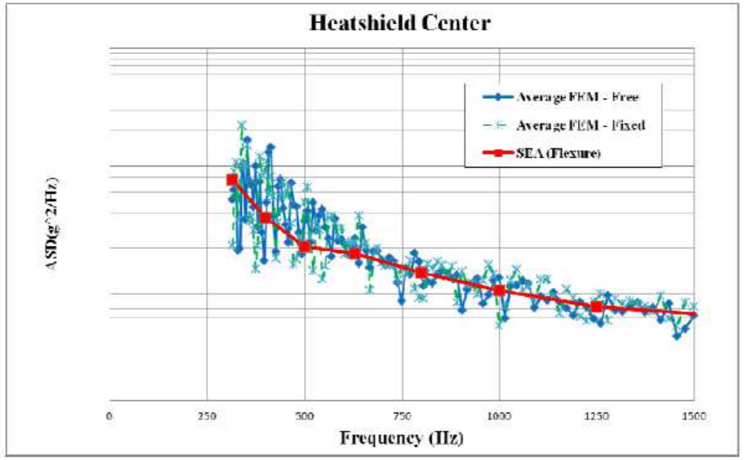
Photos: NASA & Lockheed Martin



Heatshield is broken into a hybrid model:

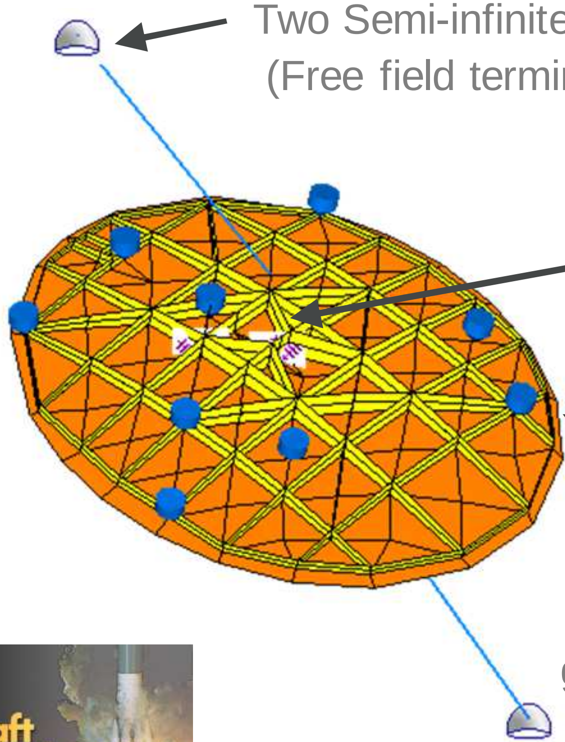
1. **SEA Center**

2. **FE shoulder**
   (the shoulder is quite stiff and it was necessary to keep it FE to model load path accurately from HS to the TAS)



Antenna design

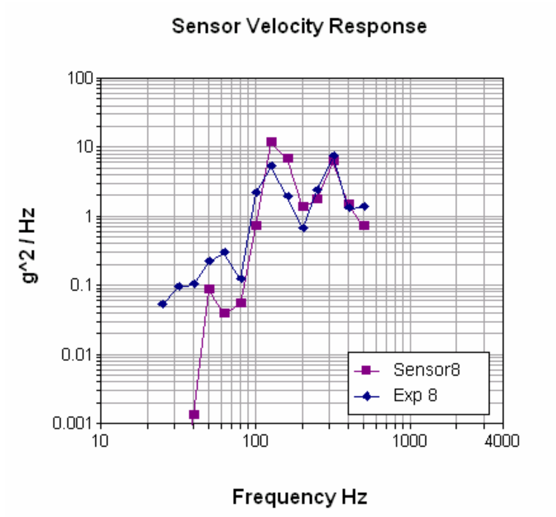
NASA Glenn Research Center

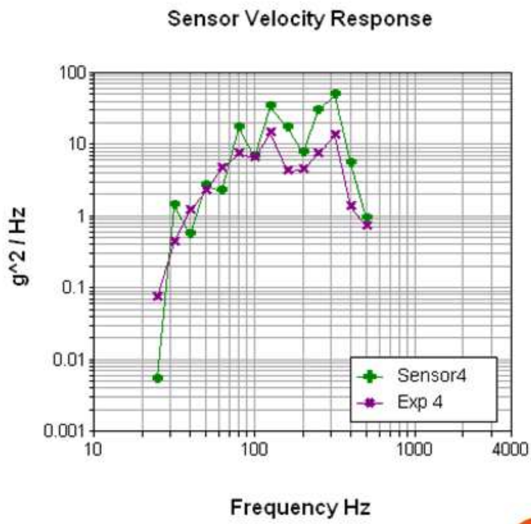


Two Semi-infinite Fluids (Free field termination)

Two Diffuse Acoustic Field Loadings, one on each side

Virtual sensors at experimental locations giving “point” responses





Satellite design

Thales Alenia Space, ESI

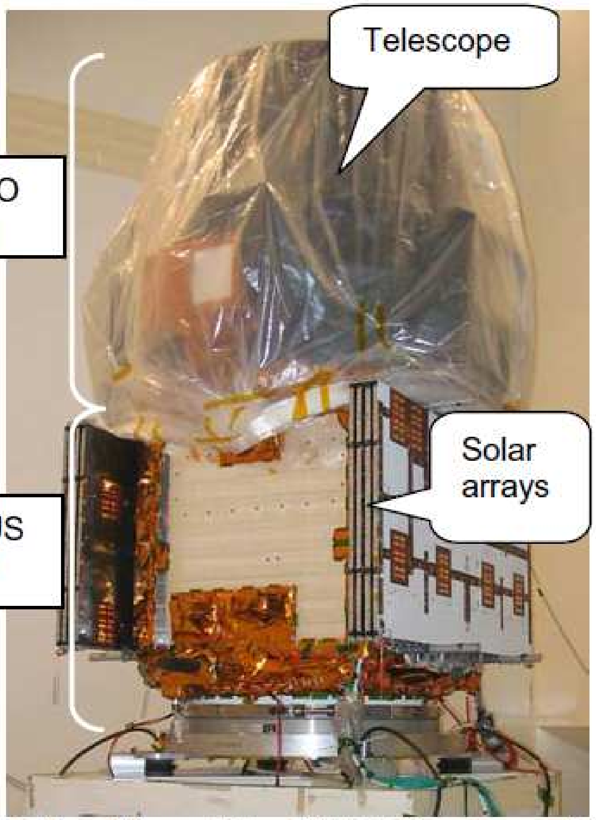


FIG 1. View of the CALIPSO spacecraft in the acoustic chamber

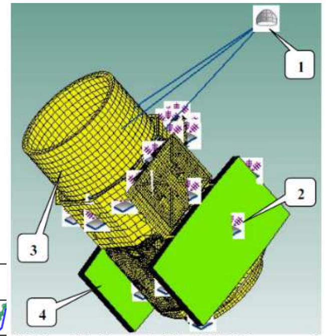


FIG 2. Hybrid model of the CALIPSO spacecraft

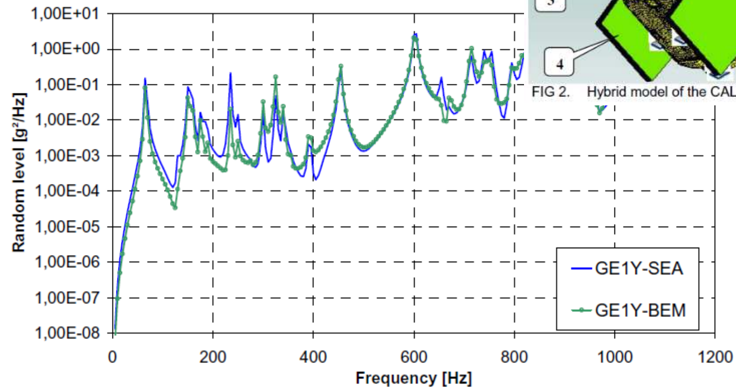


FIG 15. Random level on the platform +Y panel : comparison between BEM/FEM and hybrid SEA FEM results

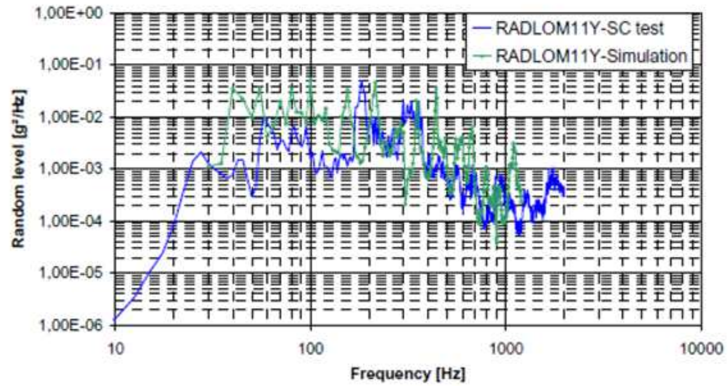


FIG 21. Random level on the RADLOM11Y accelerometer (unit mounted on the payload +Y side)

Aircraft design

NASA, Boeing, ESI

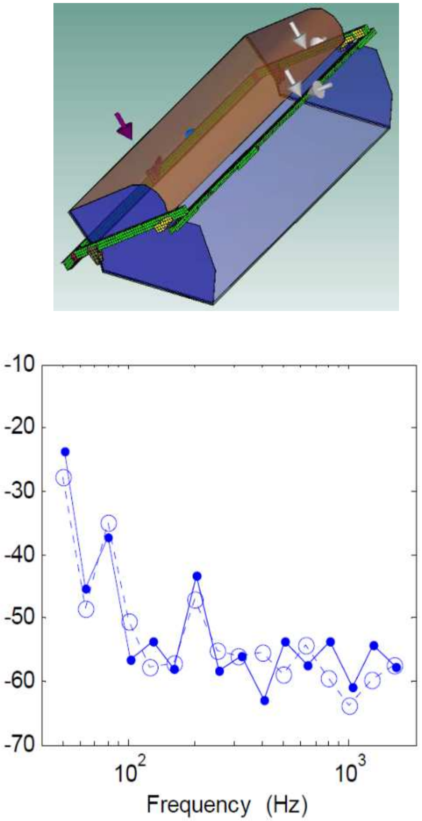


Figure 3. RMS velocity response at a point of the frame. Experimental (solid) and predicted (dotted) response, when loading at the end of the tie rod.

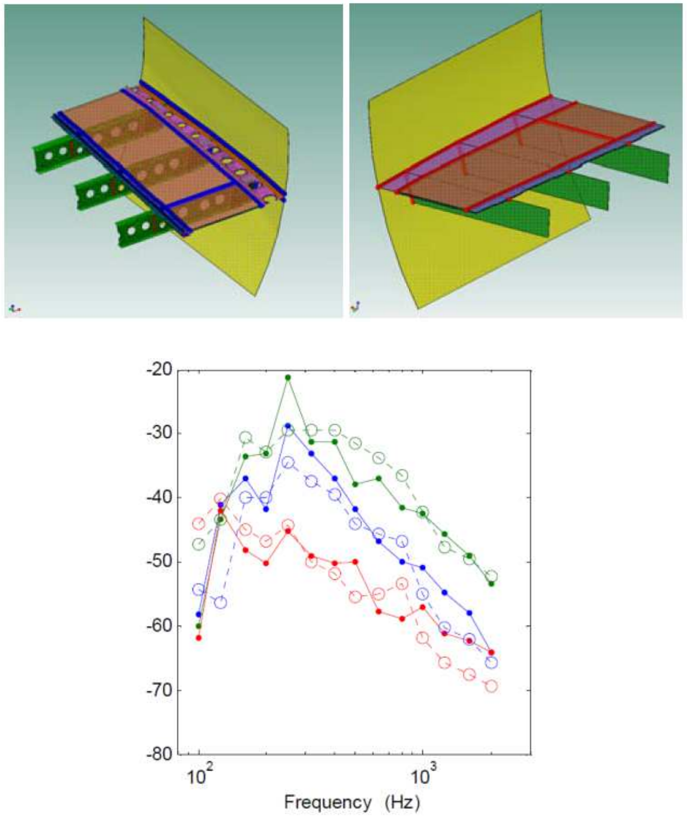


Figure 10. Velocity response of sidewall and floor panels to "rain-on-the-roof" loading on the top panel. Experimental (solid) and predicted by Hybrid (dotted).

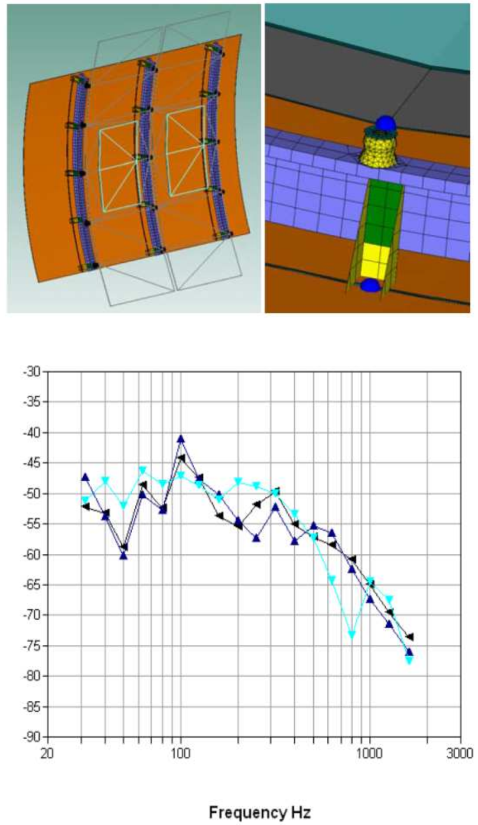
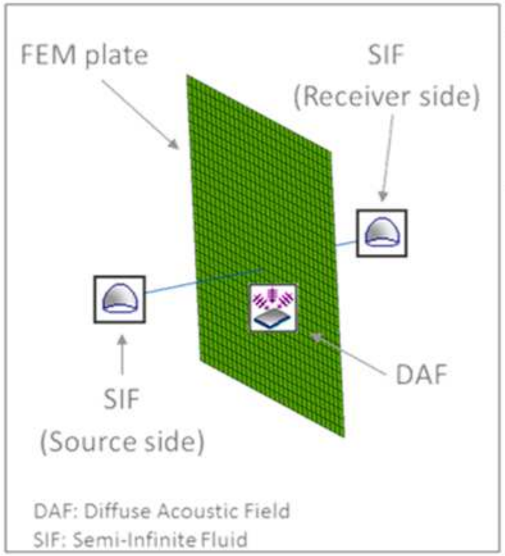


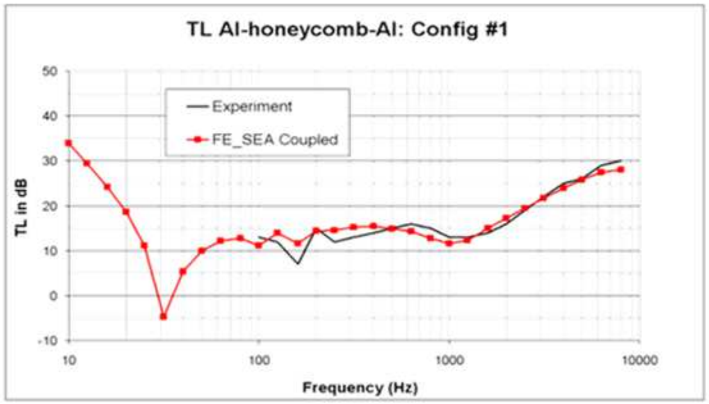
Figure 19 - Velocity response of the trim panels to a "rain-on-the-roof" excitation on the skin. Predicted response (light blue) and two experimental results.

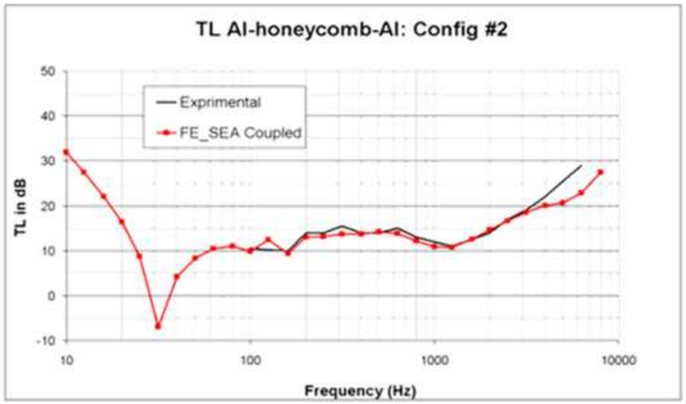
Aircraft Composite panel Transmission Loss

ESI



		Configuration 1	Configuration 2
Face Sheet (Isotropic Material)	Thickness (d)	5.842×10^{-4} m	4.572×10^{-4} m
	Density (ρ)	1716 kg/m^3	1778 kg/m^3
	Young's Modulus (E)	6.128×10^{10} Pa	1.523×10^{10} Pa
	Poisson's Ratio (ν)	0.143	0.142
	Loss factor (η)	0.05	0.05
Nomex Core (Orthotropic Material)	Thickness (d)	0.9017×10^{-2} m	1.905×10^{-2} m
	Density (ρ)	128.1 kg/m^3	48.1 kg/m^3
	Young's Modulus (E_{xx})	6.895×10^{5} Pa	6.895×10^{5} Pa
	Young's Modulus (E_{yy})	6.895×10^{5} Pa	6.895×10^{5} Pa
	Young's Modulus (E_{zz})	5.792×10^{8} Pa	1.310×10^{8} Pa
	Shear Modulus (G_{yz})	7.033×10^{7} Pa	2.550×10^{7} Pa
	Shear Modulus (G_{zx})	1.570×10^{8} Pa	4.900×10^{7} Pa
	Shear Modulus (G_{xy})	6.985×10^{5} Pa	6.985×10^{5} Pa
	Poisson's Ratio (ν_{yz})	0.01	0.01
	Poisson's Ratio (ν_{zx})	0.01	0.01
	Poisson's Ratio (ν_{xy})	0.50	0.50
	Loss factor (η)	0.05	0.05





High speed train design

Alstom, ESI

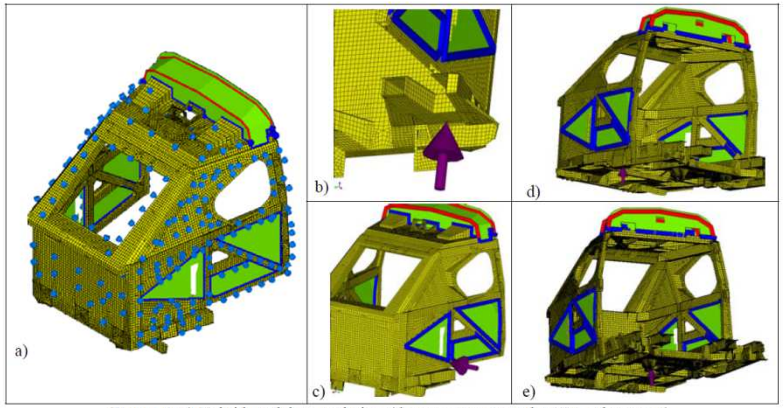


Figure 6: a) Hybrid model general view (the green areas are the SEA subsystems).
b) Input point on the lower side. c) Input point on the left lateral side.
d) Input point on the antiyaw position. e) Input point on the gearbox position.

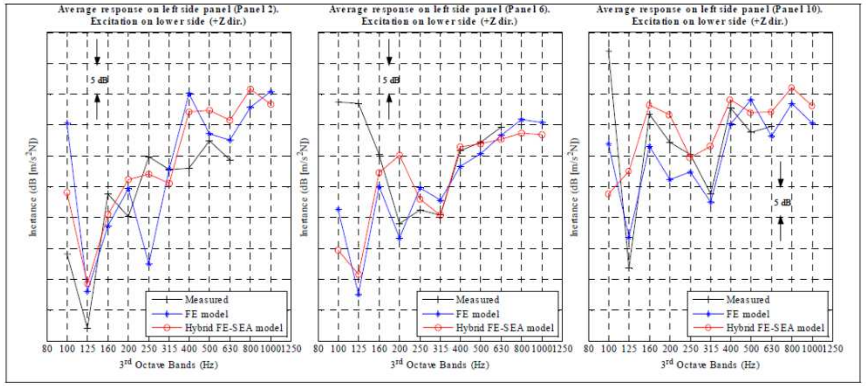


Figure 7: Results for Configuration 1. Comparison for the averaged cross-inertance (measured, calculate by FE and hybrid) at three lateral panels between 100 and 1000 Hz. Input on the lower side of the cabin in vertical direction.

Elevator design

Kingdom tower:
First 1000m high tower

- Elevators designed by Kone
- Kone is evaluating „FE/SEA Coupled“ for structural and acoustic excitation
- Also investigating „CFD/VA coupling“ for turbulent flow excitation due to high speed of elevators

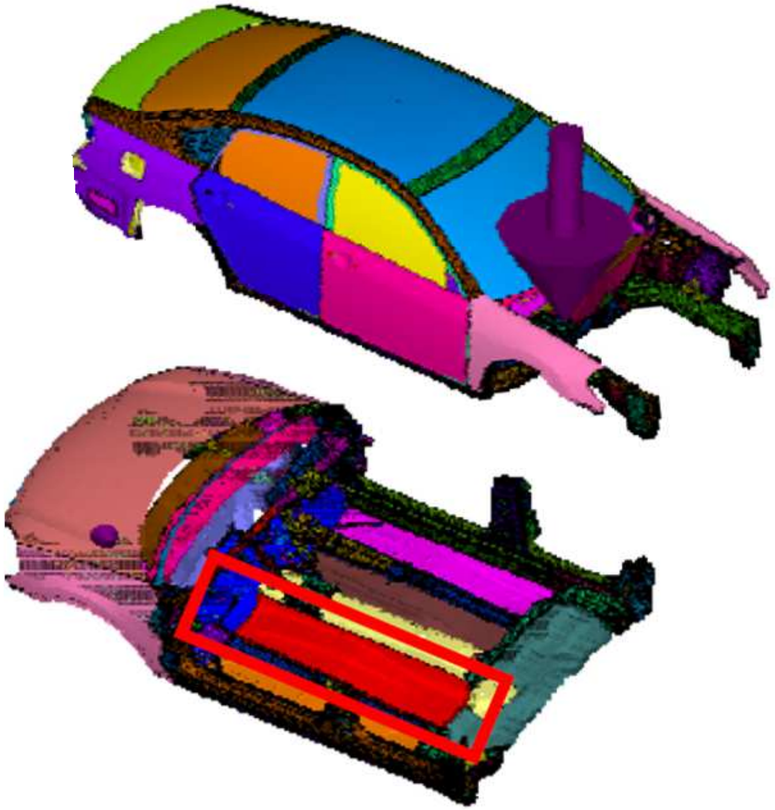
http://www.skyscrapercenter.com/jeddah/kingdom-tower/2

Submarine design

BAE Systems, Rolls Royce, Fraiser nash, Thales

Full vehicle analysis - Structureborne

Nissan: partitionning structure in FE and SEA



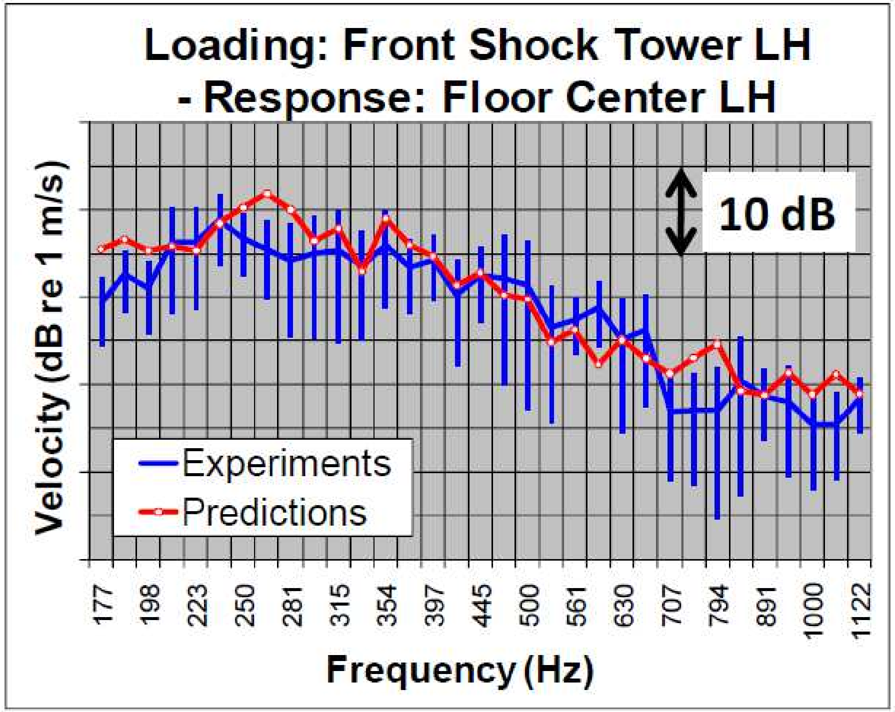
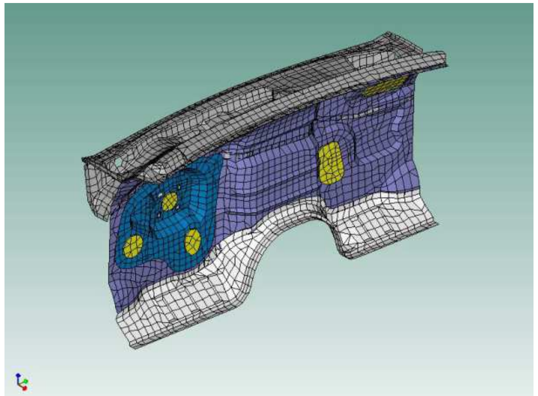
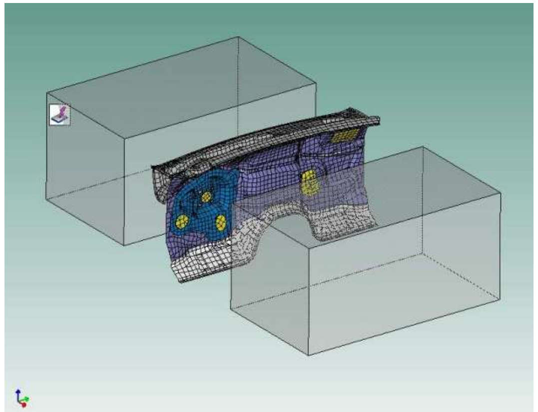


Figure 21. Velocity response of the floor center (front suspension exc.) - Hybrid vs experimental.

Dash Transmission Loss

GM, ESI





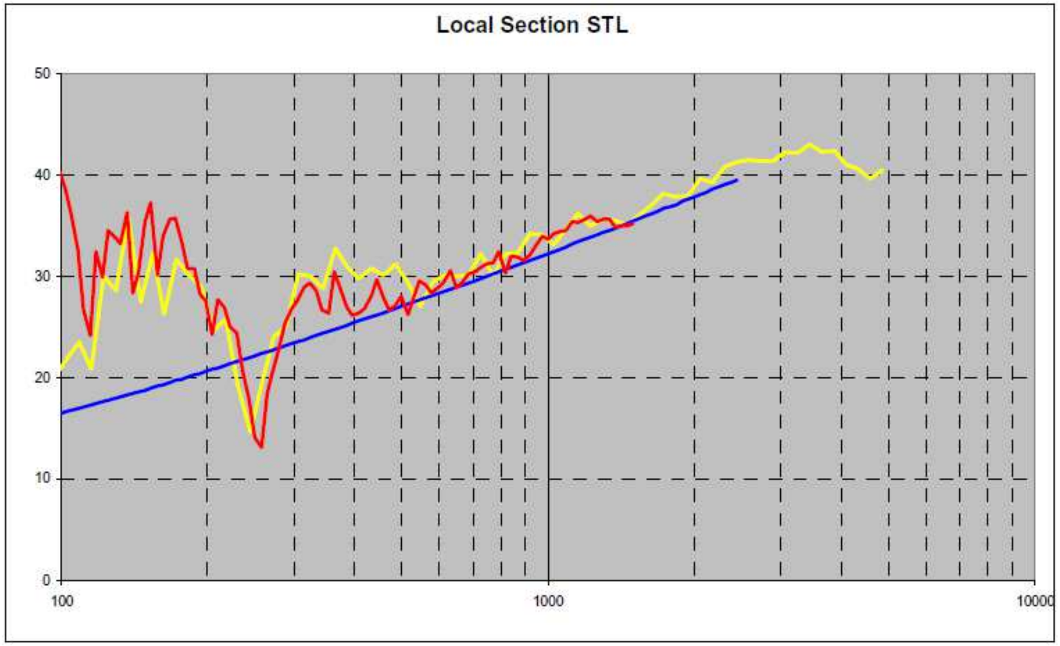
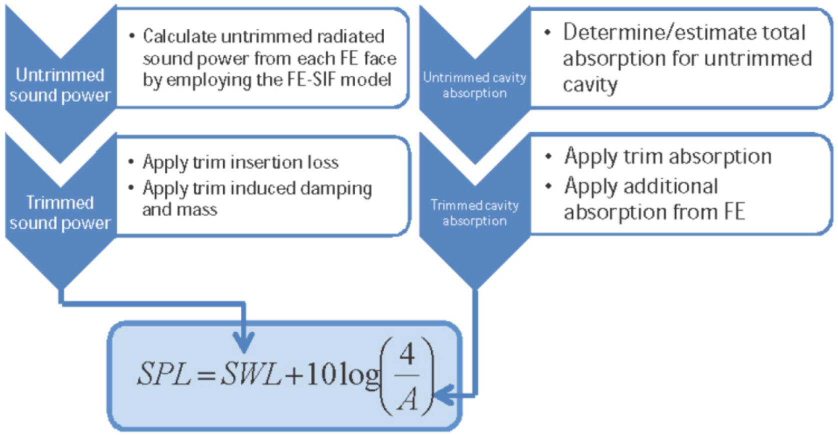
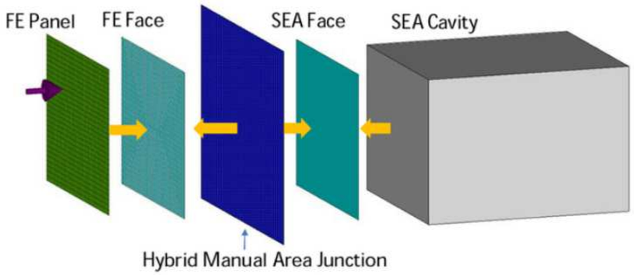


Figure 11. TL of front of dash middle section. Legend: red curve = Hybrid model; blue curve = mass law for average panel thickness; yellow curve = test.

Full vehicle analysis

GM: modeling full structure in FE





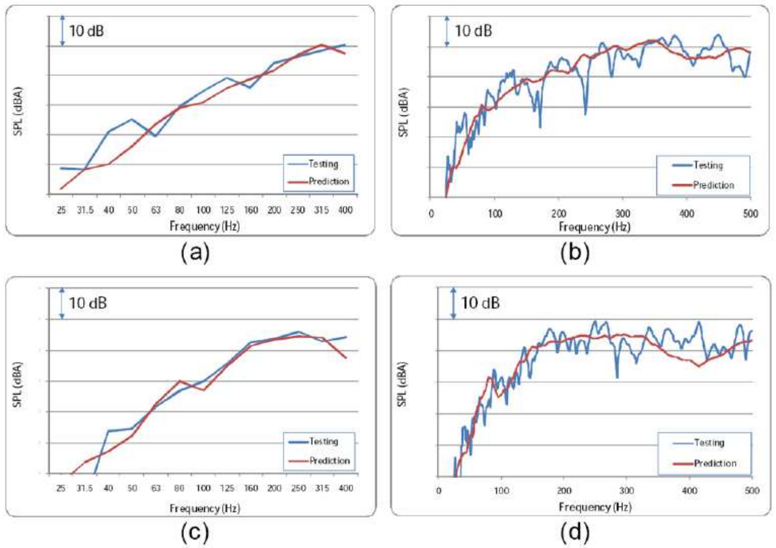
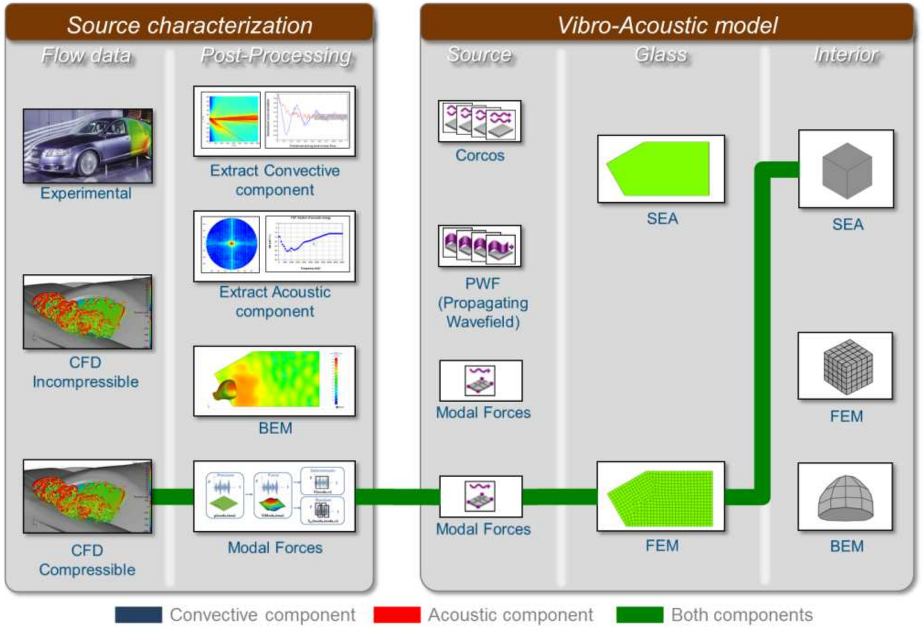
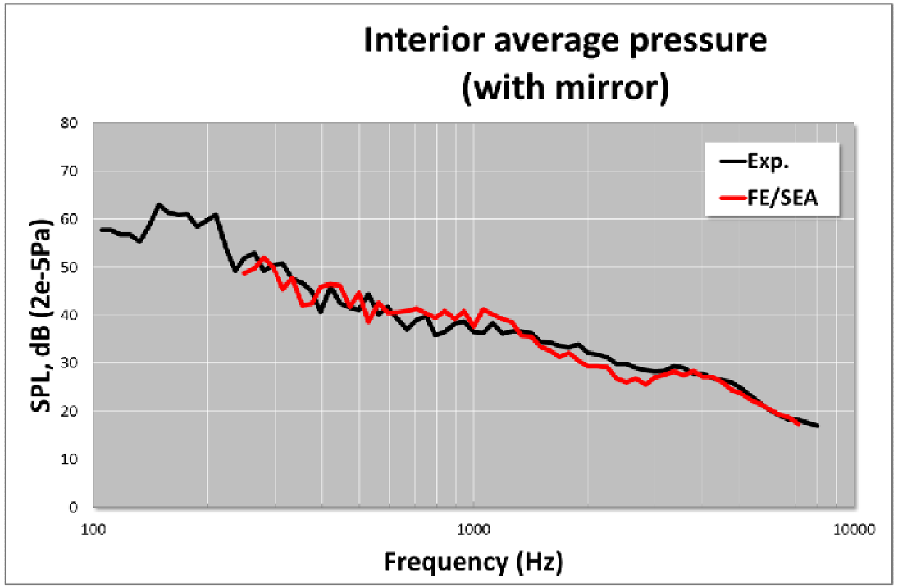


Figure 9. Interior acoustics response: carpet, door trim, garnish trim, rear seat, and headliner in place, (a) a unit force in x direction at right strut tower, 1/3 octave bandwidth; (b) a unit force in x direction at right strut tower, 5 Hz bandwidth; (c) a unit force in y direction at left rear lateral link, 1/3 octave bandwidth; (d) a unit force in y direction at left rear lateral link, 5 Hz bandwidth.

Wind noise: Coupling CFD with FE/SEA

German Working Group: Audi, Daimler, Porsche, VW and ESI



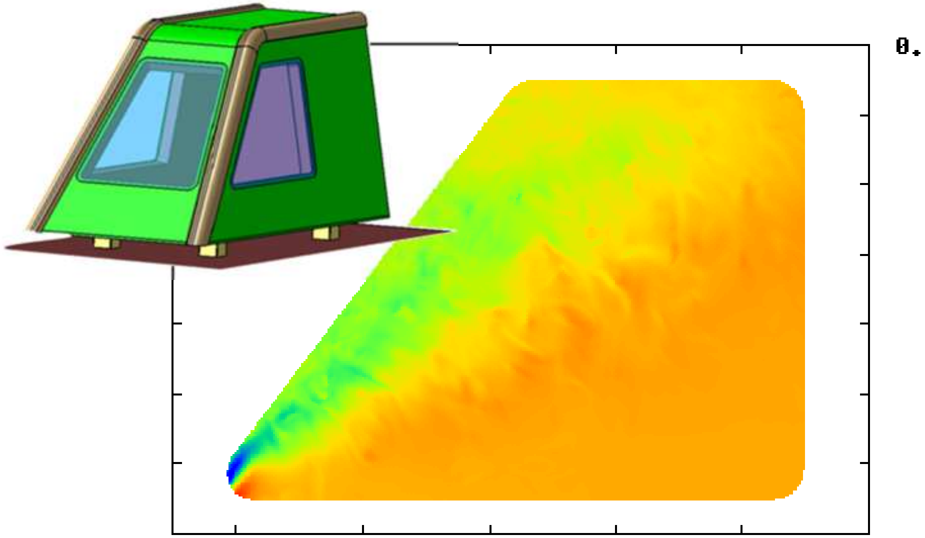


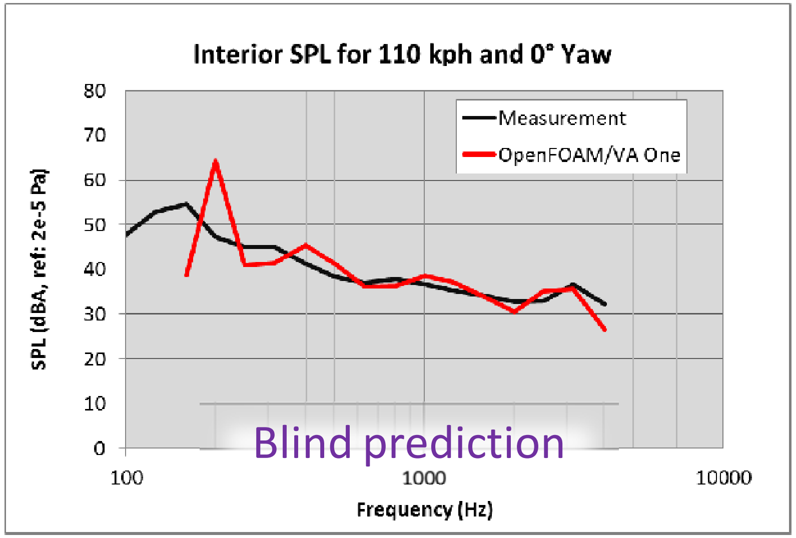
- Time domain CFD pressure fluctuation…
- Converted into modal forces projected onto FE modes of glass…
- Connected to SEA interior cavity
- Fast and accurate prediction of interior SPL

Wind noise: Coupling CFD with BEM and FE/SEA for *Hyundai Motor Corporation*

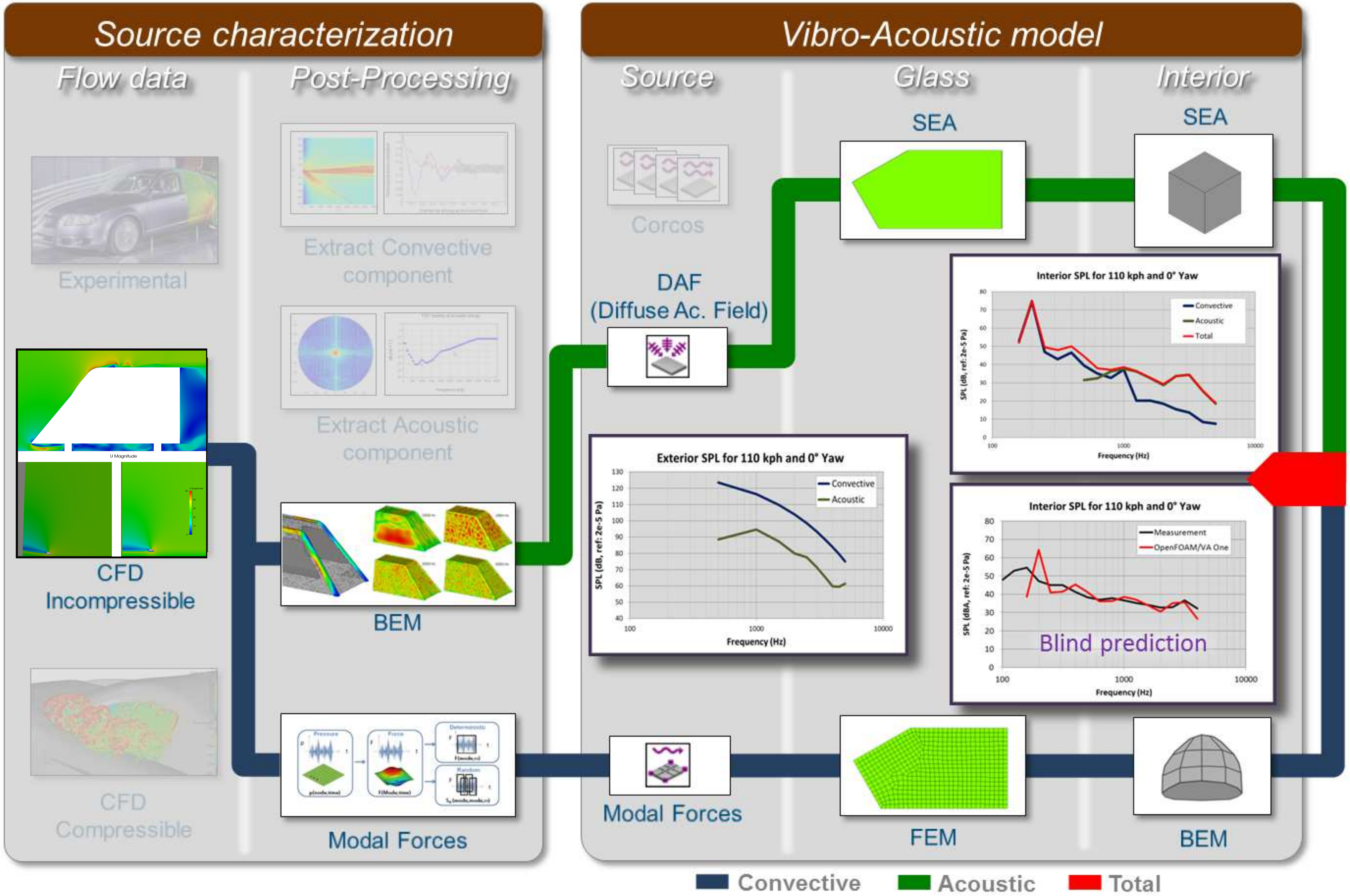
Progressive aeroacoustics and aero-vibroacoustics validation programme since 2011

- **BMT1** – *External aerodynamics and side-window aeroacoustics spectral characterization*
- **BMT2** – *Sunroof buffeting; effects of aerodynamic and interior structure damping*
- **BMT3** – *Internal noise transmission; variable speed and yaw conditions*
- **BMT4** – *Internal noise transmission; variable A-pillar, w/wo mirror designs*



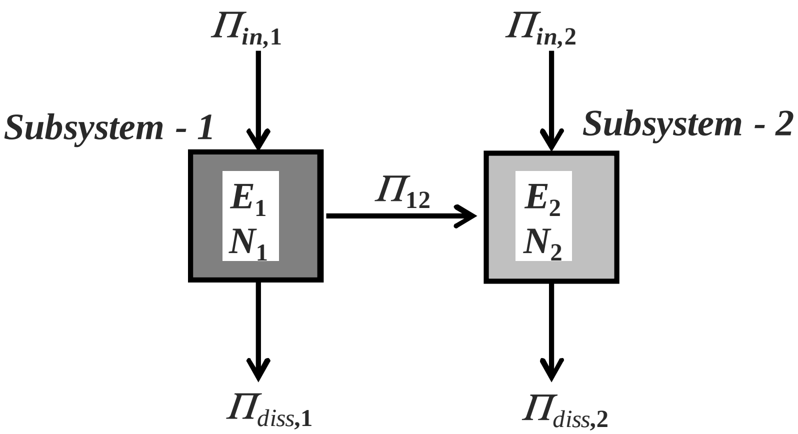


AVA Methodologies



What is SEA?

- Statistical Energy Analysis (SEA) is a method for studying diffusion of acoustic and vibration energy in a system.
- At high frequencies modes of a system become localized to various subsystems
- Flow of vibrational energy between coupled subsystems proportional to difference in modal energies (average energy per mode).
- By applying principle of conservation of energy can derive a set of power balance equations which govern response of a system in a given frequency band:

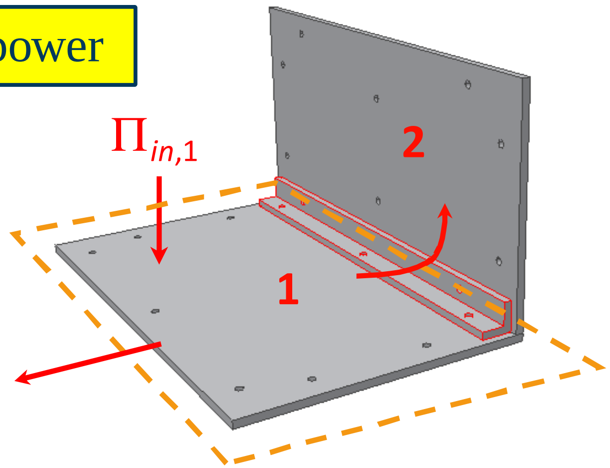


$$P_{in} = P_{out}$$

$$P_{out} = P_{transmitted} + P_{dissipated}$$

SEA equations for two subsystems

Input power



$\Pi_{diss,1} = \omega\eta_1 E_1$

Damping loss factor

Coupling loss factor

$\Pi_{coupling,12} = \omega n_1 \eta_{12}(E_1/n_1 - E_2/n_2)$

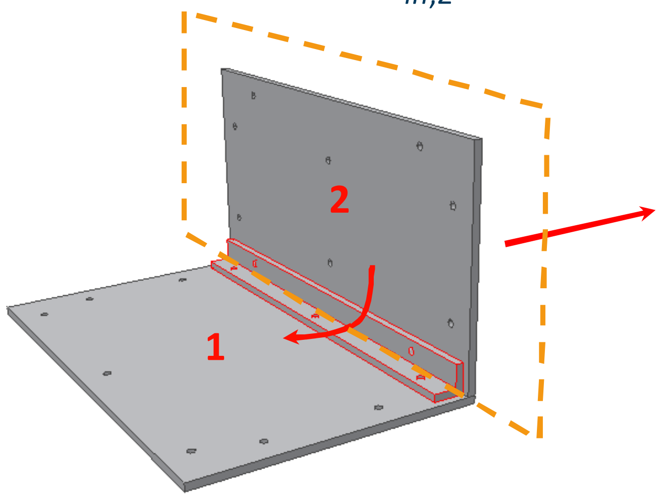
Modal density

$$\Pi_{in,1} = \Pi_{diss,1} + \Pi_{coupling,12}$$

Power balance equation for subsystem 1

SEA equations for two subsystems

$$\Pi_{in,2} = 0$$



$$\Pi_{diss,2} = \omega \eta_2 E_2$$

$$\Pi_{coupling,21} = \omega n_2 \eta_{21} (E_2/n_2 - E_1/n_1)$$

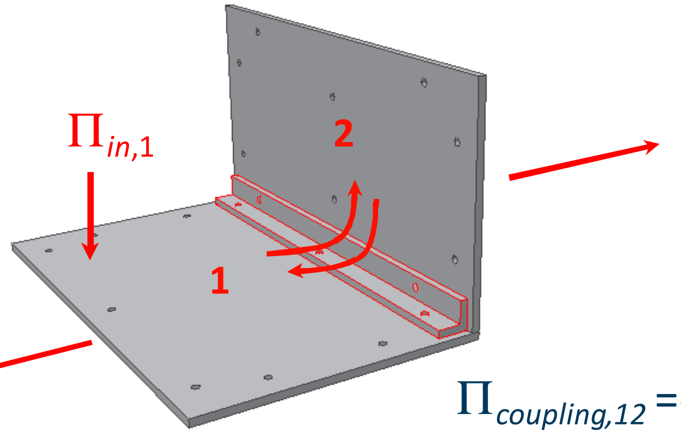
$$\Pi_{in,2} = \Pi_{diss,2} + \Pi_{coupling,21}$$

Power balance equation for subsystem 2

SEA equations for two subsystems

System with millions of nodal dofs has one energy dof per subsystem

$\Pi_{in,1}$



$\Pi_{diss,2} = \omega\eta_2 E_2$

$\Pi_{diss,1} = \omega\eta_1 E_1$

$\Pi_{coupling,12} = \omega n_1 \eta_{12}(E_1/n_1 - E_2/n_2)$

$\Pi_{coupling,21} = \omega n_2 \eta_{21}(E_2/n_2 - E_1/n_1)$

$$\begin{bmatrix} \Pi_{in,1} \\ 0 \end{bmatrix} = \omega \begin{bmatrix} n_1(\eta_1 + \eta_{12}) & -n_1\eta_{12} \\ -n_2\eta_{21} & n_2(\eta_2 + \eta_{21}) \end{bmatrix} \begin{bmatrix} E_1/n_1 \\ E_2/n_2 \end{bmatrix}$$

The SEA equations

SEA equations for k subsystems

$$\omega\begin{bmatrix} n_1\left(\eta_{11}+\sum_{i\neq 1}\eta_{1i}\right) & -\eta_{21}n_2 & \cdots & -\eta_{N1}n_N \\ -\eta_{12}n_1 & n_2\left(\eta_{22}+\sum_{i\neq 1}\eta_{2i}\right) & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ -\eta_{1N}n_1 & \cdots & \cdots & n_N\left(\eta_{NN}+\sum_{i\neq 1}\eta_{Ni}\right) \end{bmatrix} \times \begin{bmatrix} \frac{E_1}{n_1} \\ \cdots \\ \cdots \\ \frac{E_N}{n_N} \end{bmatrix} = \begin{bmatrix} P_{in,1} \\ \cdots \\ \cdots \\ P_{in,N} \end{bmatrix}$$

Vector of power excitation

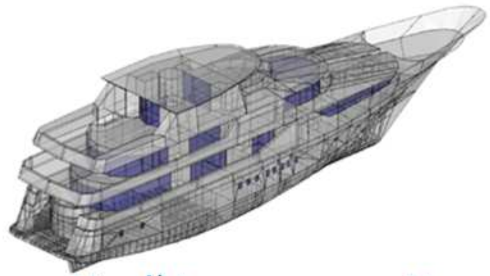
Vector of unknown subsystem energies

Matrix of coupling and damping loss factors

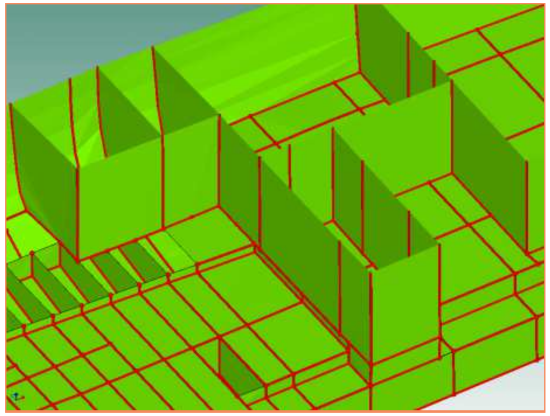
- Observations:
  - Small matrix (k x k for k subsystems)
  - Using N_i the matrix is symmetric
  - Usually well-conditioned
  - No information on natural frequencies and modes shapes
  - Resolving only updates small parts, solves quickly

$$\omega[\eta]\langle E\rangle = \langle P\rangle$$

Definition of a SEA Subsystem



Subsystem: A group of similar modes (e.g. flexural, in-plane, acoustical) in some section of the system that are capable of storing, transmitting or dissipating significant amount of energy.



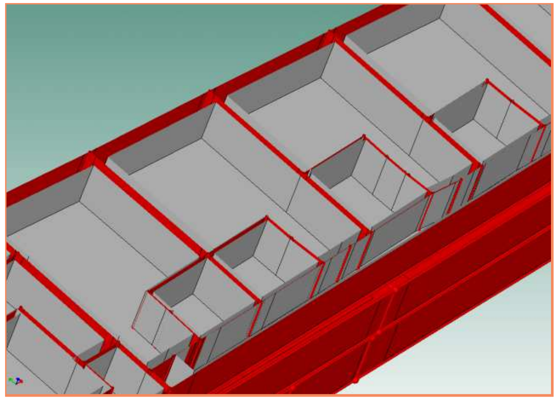
Structural Subsystem Energy:

Wavefields: Flexural,Shear & Extensional

Panel mass

$$E_1 = \langle V^2 \rangle_{sp}\, m$$

Mean square vibration



Acoustic Subsystem Energy:

Wavefields: Pressure

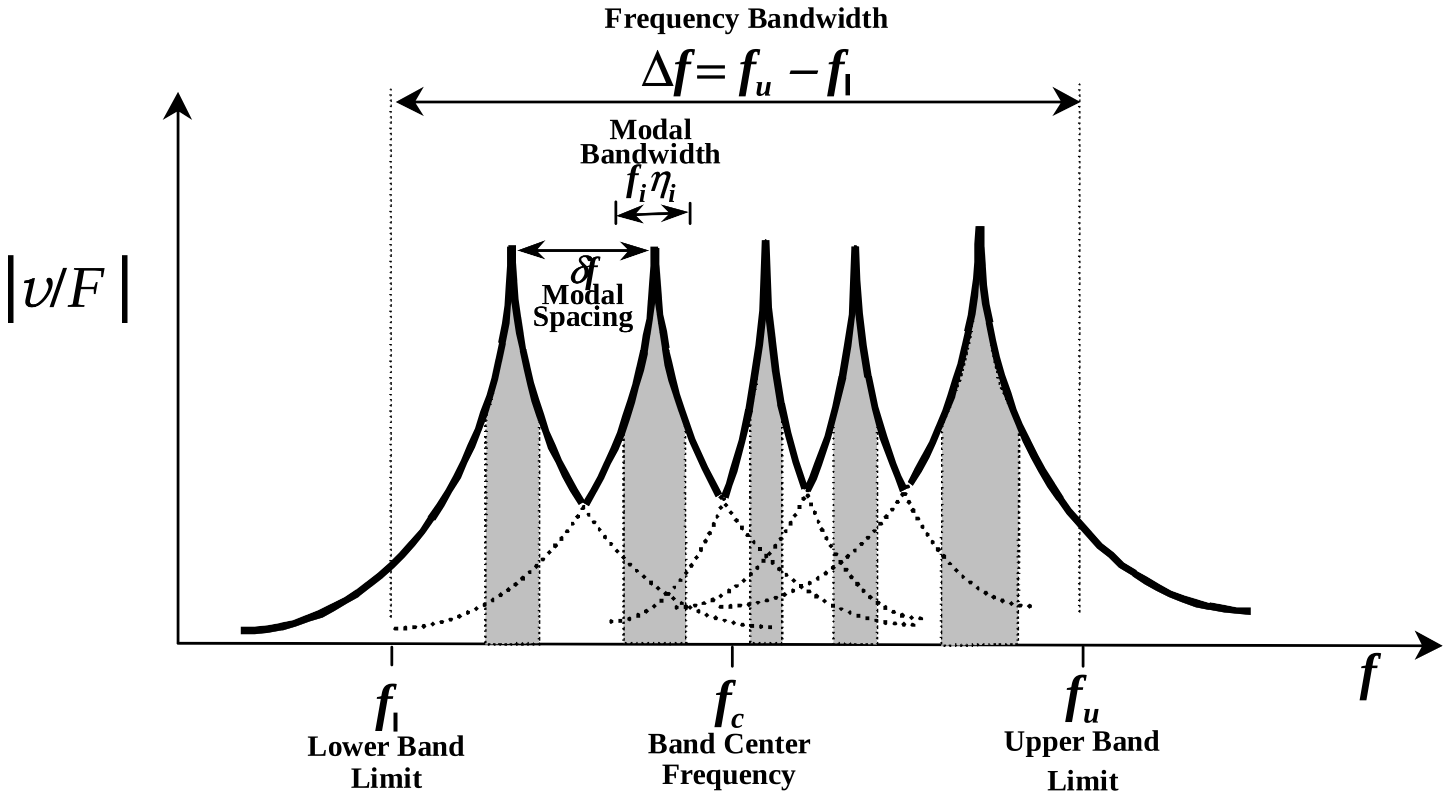
Cavity volume

$$E_2 = \langle P^2 \rangle_{sp}\, V/(\rho c^2)$$

Mean square pressure

Fluid properties

Energy storage:
Modes in Band and Modal Density



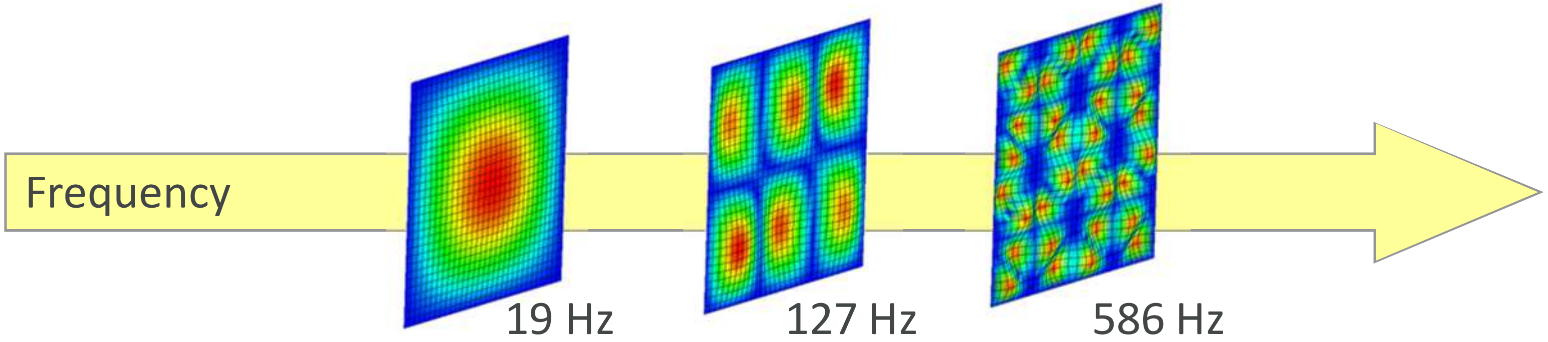
Modes in Band $N(f) = \text{number of modes in } \Delta f$

Modal Density $n(f) = \dfrac{N(f)}{\Delta f} = 2\pi n(\omega)$

Modes representation

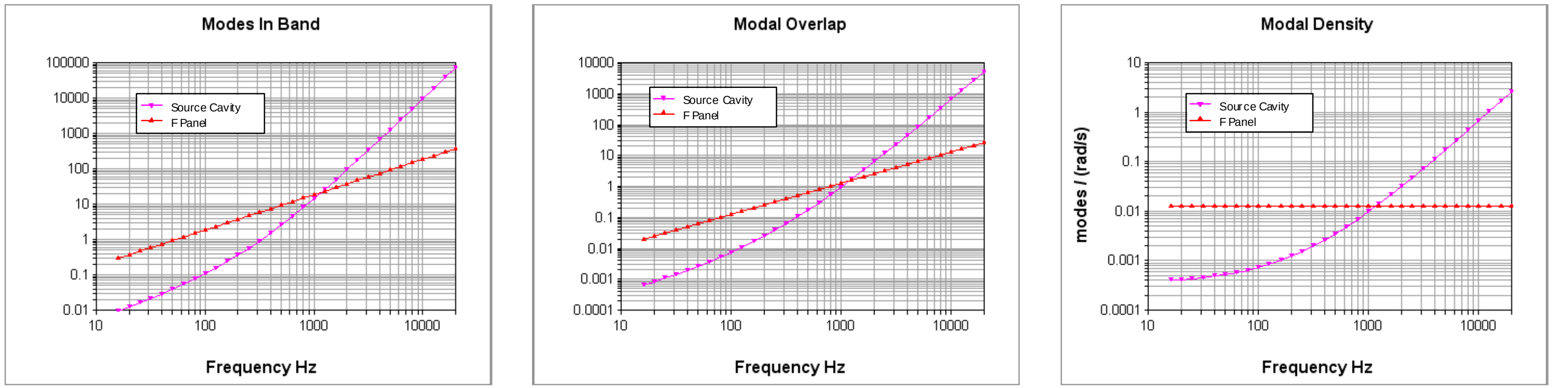
FEM:

Modes are represented by eigen values and eigen vectors



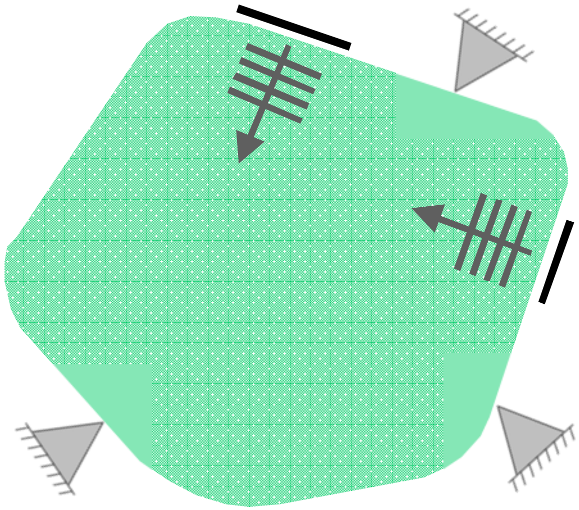
SEA

Modes are represented by modal density



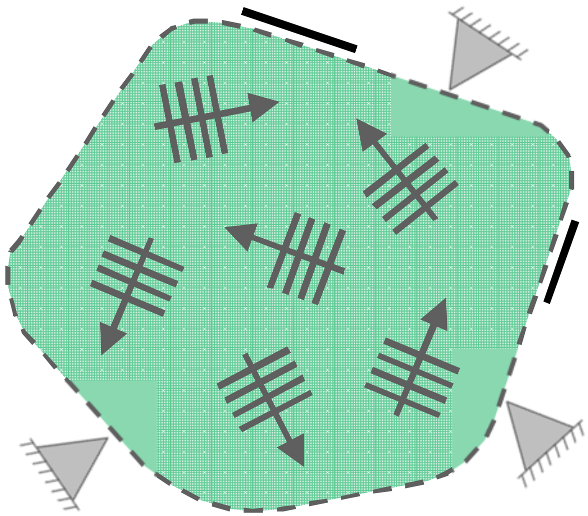
Introduction to FE/SEA Coupled

Each SEA subsystem represented in terms of superposition of a direct field and a reverberant field.



Direct field

Component of response associated with direct field radiation from connections - deterministic



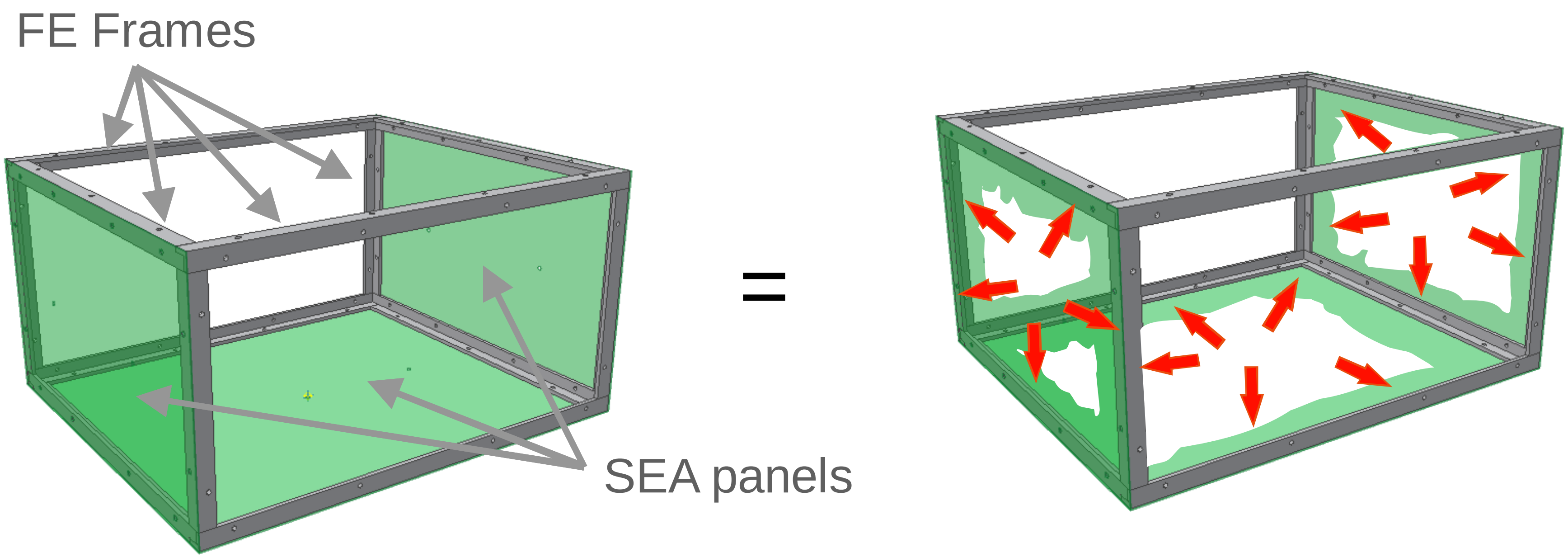
Reverberant field

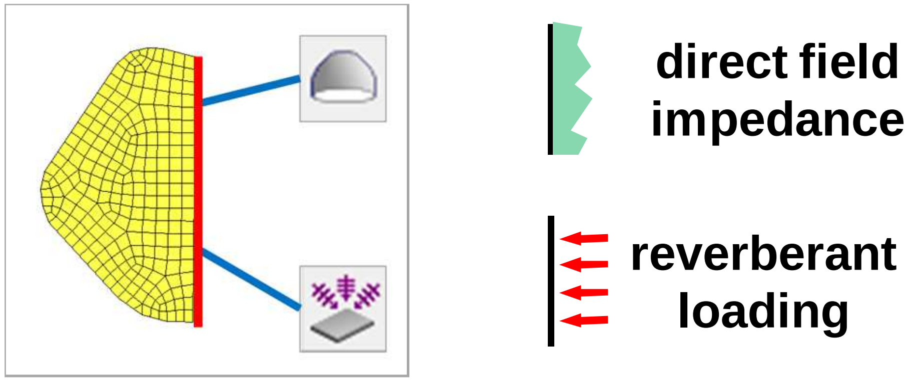
Component of response associated with reflections from boundaries of subsystem and blocked connections – statistical

get it right®

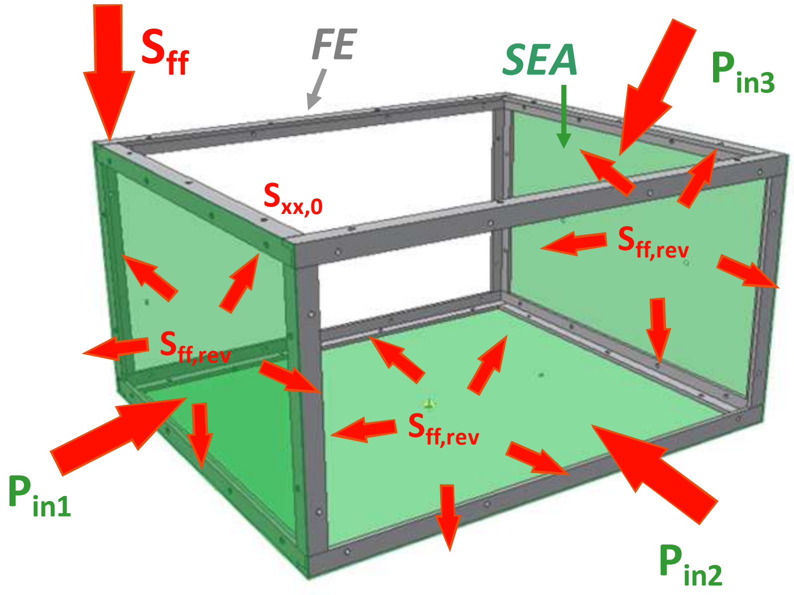
Introduction to FE/SEA Coupled

Direct vs reverberant field





Full frequency analysis



Response due to FE external excitation

$$\left[\mathbf{D}_0 + \sum_i \mathbf{D}_{i,dir}\right]\{\mathbf{x}\} = \{\mathbf{f}\}$$

Dynamic stiffness of SEA subsystem

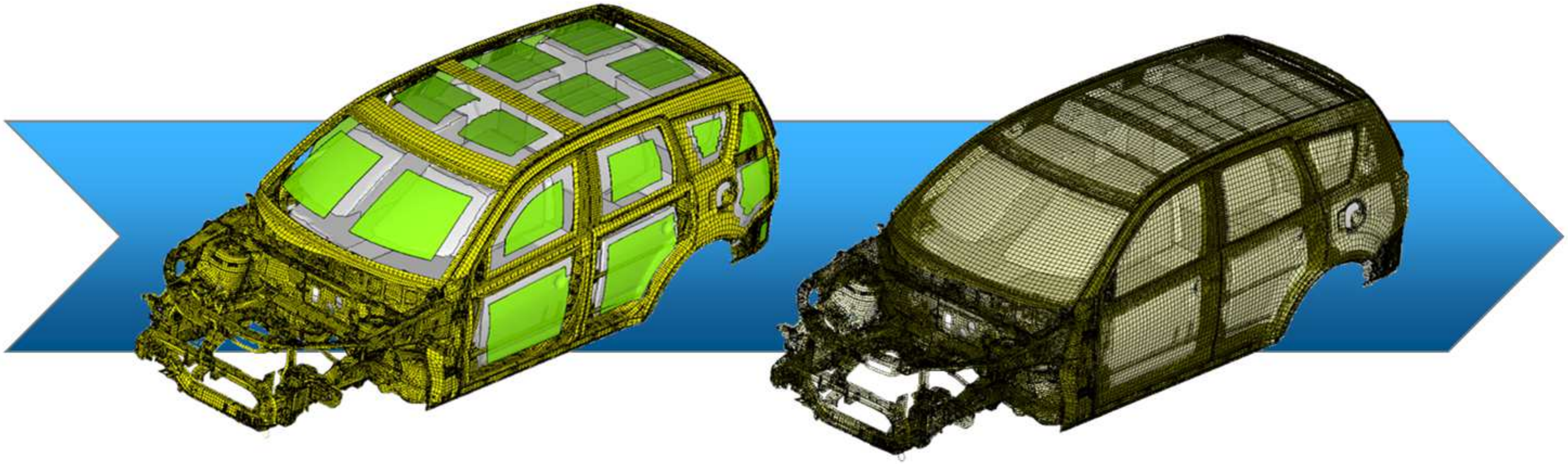
Total response is sum of response to FE external excitation AND reverberant loading from each SEA subsystem

$$\mathbf{S}_{xx} = \mathbf{S}_{xx,0} + \sum_i \mathbf{S}_{xx,rev,i} = \mathbf{R}\left[\mathbf{S}_{ff,0} + \sum_i \mathbf{S}_{ff,rev,i}\right]\mathbf{R}^H$$

where $\mathbf{R} = \left[\mathbf{D}_0 + \sum_i \mathbf{D}_{i,dir}\right]^{-1}$

Evolution of the use of „FE/SEA Coupled“

In the automotive industry

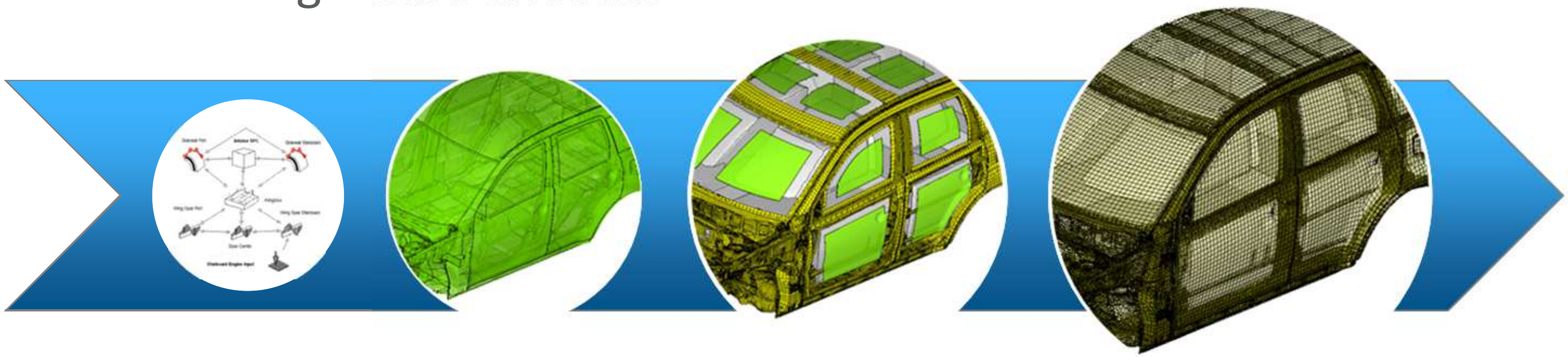


- Structure in FE and SEA
- Cavity/NCT in SEA
- Model building slow (weeks)
- Computation fast (~4 hours)
- VA Expert needed

- Structure in FE only
- Cavity/NCT in SEA
- Model building fast (days)
- Computation slower (~16 hours)
- Junior engineer needed

Conclusion

- FE/SEA Coupled has been validated in various industries
- It is widely used on a day to day basis at numerous customers
- It reduces computation time
- It opens up new possibilities where FE was quite limited
- Automation of model building process is under way
- Possible today to create Fully-Coupled Multi-Domain models which include several methods
- Promising future ahead…



THANK YOU FOR YOUR ATTENTION