Up2HF
Summer School

SEA Prediction and Analysis of Complex Industrial Systems

Dr. Gérard Borello

InterAC, 10 impasse Borde-Basse, ZA La Violette, F-31240 L'Union
33 (0)5 61 09 47 45 gerard.borello@interac.fr

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

1- Introduction

- SEA is a well-suited method to analyze the complex broadband dynamic of car, train, aircraft, ships and most of vibrating industrial systems of which vibratory response is dominated by resonant modes.




- To build **robust SEA models**, representative of the actual behavior**, three major steps** are required:
  - **substructuring into "SEA compatible" subsystems,**
  - **selecting theoretical description of subsystems and junctions from SEA software library,**
  - **entering description of actual operating loads.**

2 - Introduction

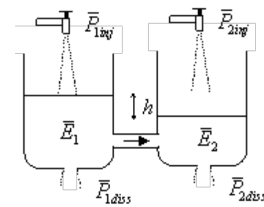
- Because of the inherent SEA-theory, assumptions, quality of outputs delivered by SEA models have to be **carefully checked**, at least when modeling new class of system where related engineering background is low.
  - **Validations** are performed with **Experimental SEA** method (**ESEA**), very efficient in correlating observed and simulated results.
  - In the **design phase** where no test data is available model, **Virtual SEA** method (**VSEA**) may replace testing as it transforms **Finite Element** (**FEM**) models of the system into SEA set of coupled subsystems, with **automatic identification** of their **partition**, **coupling loss factors** and **modal density**.
- Examples of industrial SEA model realization in different domains (car, building acoustic, aerospace…) are presented with their validation.
  - EXAMPLES 1: Prediction of acoustic and shock responses of launch vehicles, rocket engines and satellites
  - EXAMPLES 2: Prediction of outer and inner radiated acoustic pressure by cars and trucks
  - EXAMPLE 3: Simulation of transmission tests of timber framed building walls

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

The SEA Method

- Direct SEA equations: the power-balanced equations between subsystems
  - Start by a partition of the dynamical domain into weakly coupled subsystems
  - Energy equilibrium of subsystems in steady-state

$$\frac{P_{in}^{i}}{\omega_c} = \eta_i E_i + \sum_{j/j\,\text{coupled to}\,i} \left[\eta_{ij} E_i - \eta_{ji} E_j \right]$$



  - Local modal densities of subsystem and Coupling Loss Factors (**CLF**) estimated by analytical models (beam, plate, shell, cavity) and wave transmission approach
  - A SEA model is then characterized by its Loss matrix made of Damping Loss Factors (**DLF**) and CLF

- Inverse SEA equations (ESEA / VSEA)
  - Loss-matrix is estimated from transfer energy matrix *Eij* between subsystems
  - *Eij* is measured by testing using calibrated excitation (known injected power)

$$\mathbf{L} = \begin{bmatrix} \eta_1 + \sum_{j_1} \eta_{1j_1} & \cdots & -\eta_{i1} & \cdots & -\eta_{N1} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ -\eta_{1i} & \cdots & \eta_i + \sum_{j_2} \eta_{ij_2} & \cdots & -\eta_{Ni} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ -\eta_{1N} & \cdots & -\eta_{1i} & \cdots & \eta_N + \sum_{j_N} \eta_{Nj_N} \end{bmatrix}$$

$$\frac{P_{in}}{\omega_c}\mathbf{I} = \mathbf{L}\cdot\mathbf{E} \Rightarrow \mathbf{L} = \mathbf{E}^{-1}\cdot\mathbf{I}\frac{P_{in}}{\omega_c}$$

Multi-modal energy response

- For a continuous system modeled as a set of modal oscillators PSD response is equal to

$$S_X(\omega) = \sum_N S_{Xi}(\omega, \omega_i)$$

- In a frequency band of width $\Delta\omega$ the band integrated response is proportional to the number of resonances in the band

$$X(\omega_c, \Delta\omega)^2 = \frac{1}{2\pi} \sum_N \left\{ \int_{\Delta\omega} S_{Xi}(\omega, \omega_i)^2 d\omega \right\} \approx \mathcal{N} \left\langle x_{i\_rms}^2 \right\rangle_i$$

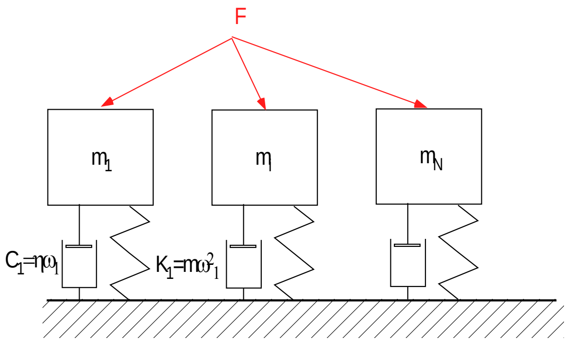
- The band integrated total energy is then equal to the sum of mean (over time) modal energies (**white energy**)

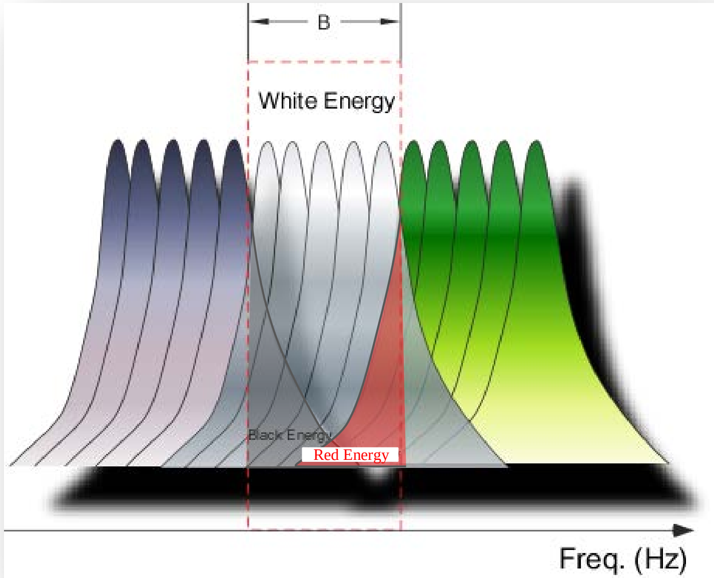
$$E = \sum E_i \approx \mathcal{N} \langle E_i \rangle_i \quad \text{with} \quad \langle E_i \rangle_i = E / \mathcal{N}$$

- The band-integrated system response can then be characterized by a statistical mean modal response of which power balanced equation are written as

$$P = \mathcal{N} \langle \eta \rangle \omega_c \langle E_i \rangle_i = \langle \eta \rangle \omega_c E$$

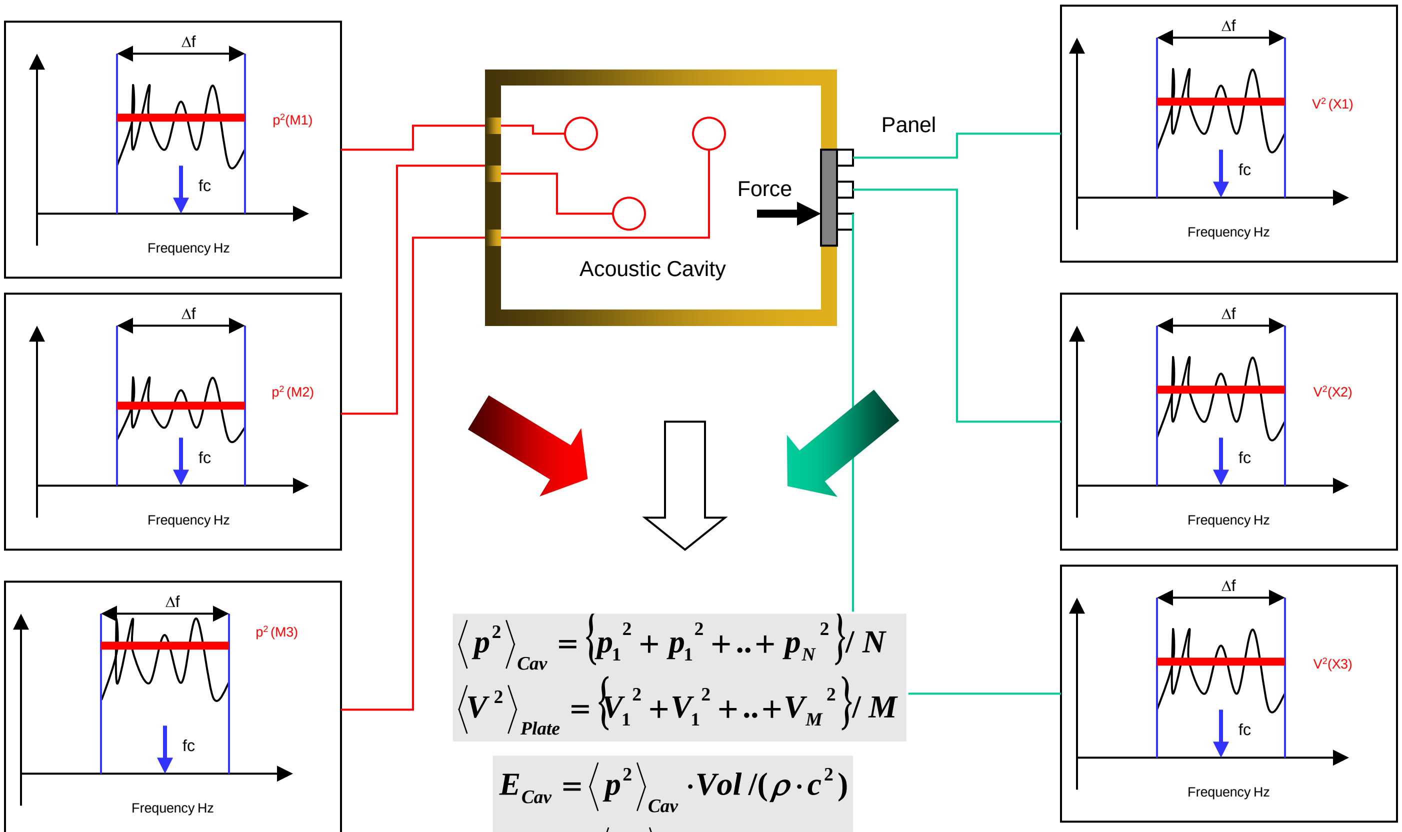
- Extra non-resonant energies non included in N are also generated (**black & red energies**)





SEA quantities vs. measurements

Space and Frequency Averaging



$$\langle p^2 \rangle_{Cav} = \{p_1^{\,2} + p_1^{\,2} + .. + p_N^{\,2}\}/\,N$$

$$\langle V^2 \rangle_{Plate} = \{V_1^{\,2} + V_1^{\,2} + .. + V_M^{\,2}\}/\,M$$

$$E_{Cav} = \langle p^2 \rangle_{Cav} \cdot Vol/(\rho \cdot c^2)$$

$$E_{Plate} = \langle V^2 \rangle_{Plate} \cdot m$$

$$\Pi_{inj} = F^2 G$$

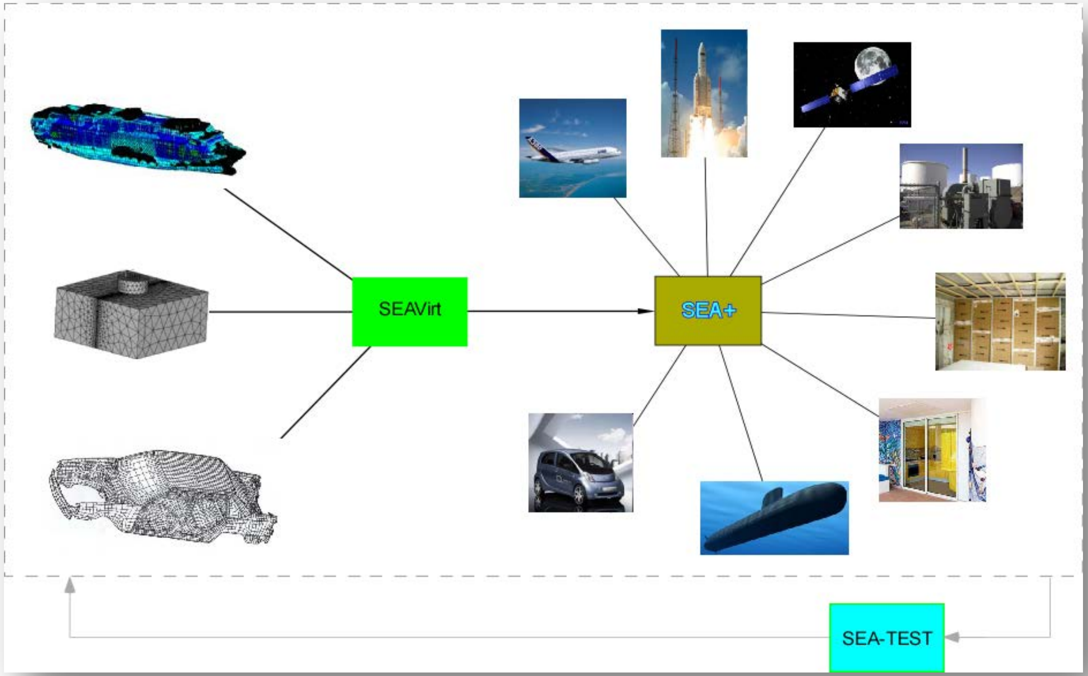
N microphones

M accelerometers

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

SEA modeling data flow and applications

- **SEA+** software is a SEA application based on a new scientific kernel developed for high-end applications with the support of aerospace and automotive industries
- **SEA+** predicts SEA parameters from
  - Analytical formulations
  - From FEM through **SEAVirt** (module of SEA+) which identifies SEA subsystems using Virtual SEA (**VSEA**)
  - From Test through **SEA-TEST** software which implements Experimental SEA (**ESEA**)

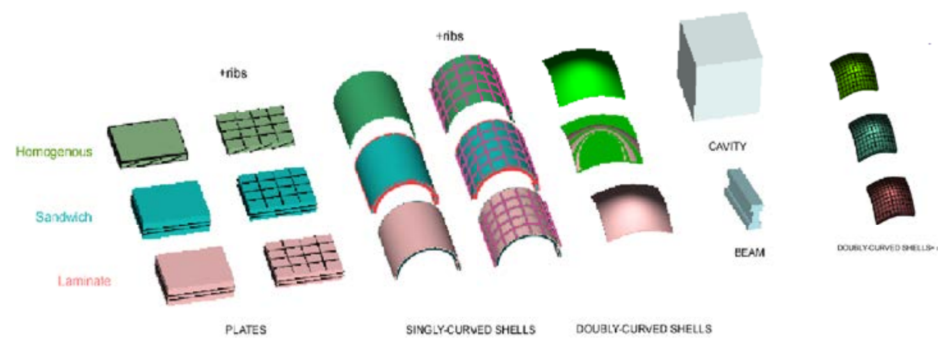


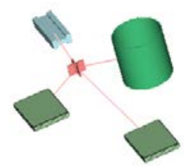
SEA+ / SEA-TEST software are distributed by SIEMENS Industry Software

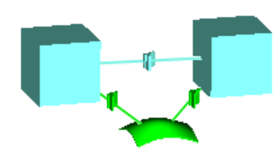
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

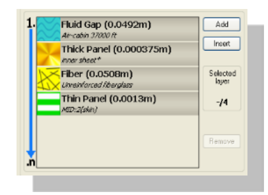
SEA+ libraries for analytical/virtual modeling

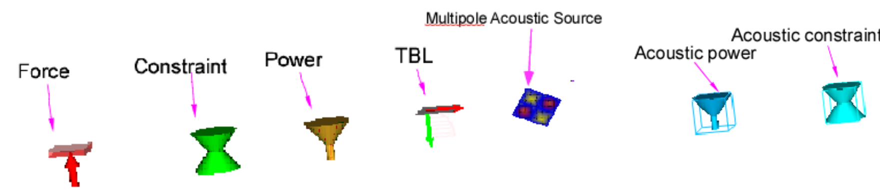
- **Analytical beam, plate and shell subsystems**
  - Homogeneous, orthotropic, ribbed
  - sandwich, orthotropic, ribbed
  - Laminate, orthotropic, ribbed
  - Support 3 wave types flexural, extensional, shear
- **Mechanical coupling of any mechanical subsystems and waves**
  - Support 3 wave-types, include joint modeling at junction
  - Point, multi-points
  - Line
  - Spatial windowing
- **Acoustic coupling**
  - Mass law, leakage through apertures, spectral transmission loss
  - Trim modeler (foam, fiber, perforated layer, thick and thin plates, thin shell, fluid gap, management of temperature and static pressure)
- **Acoustic-to-structure coupling**
  - Numerical radiation efficiency computation with heavy fluid added mass
- **Power sources**
  - User-defined Power spectra, constraint energy, force
  - Diffuse and incident acoustic wave
  - TBL
  - Multipole Acoustic source
- **Shock Response Spectrum and time history from a shock source**
  - Shock source generator for launch vehicles and spacecrafts
    - clampband, pyrozip line & point
- **Acoustic synthesis method**
  - FFT connectors, Power Sound Filter, Active Sound probe, Infinite Fluid Volume
- **3D Narrow band force**
- **Thermal noise source**

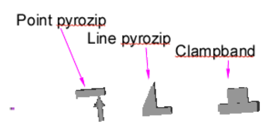


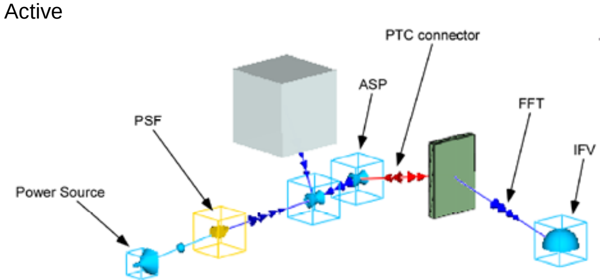


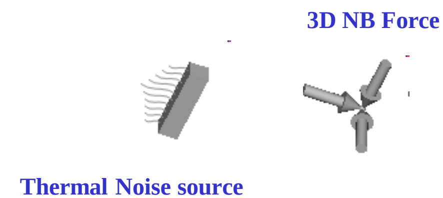






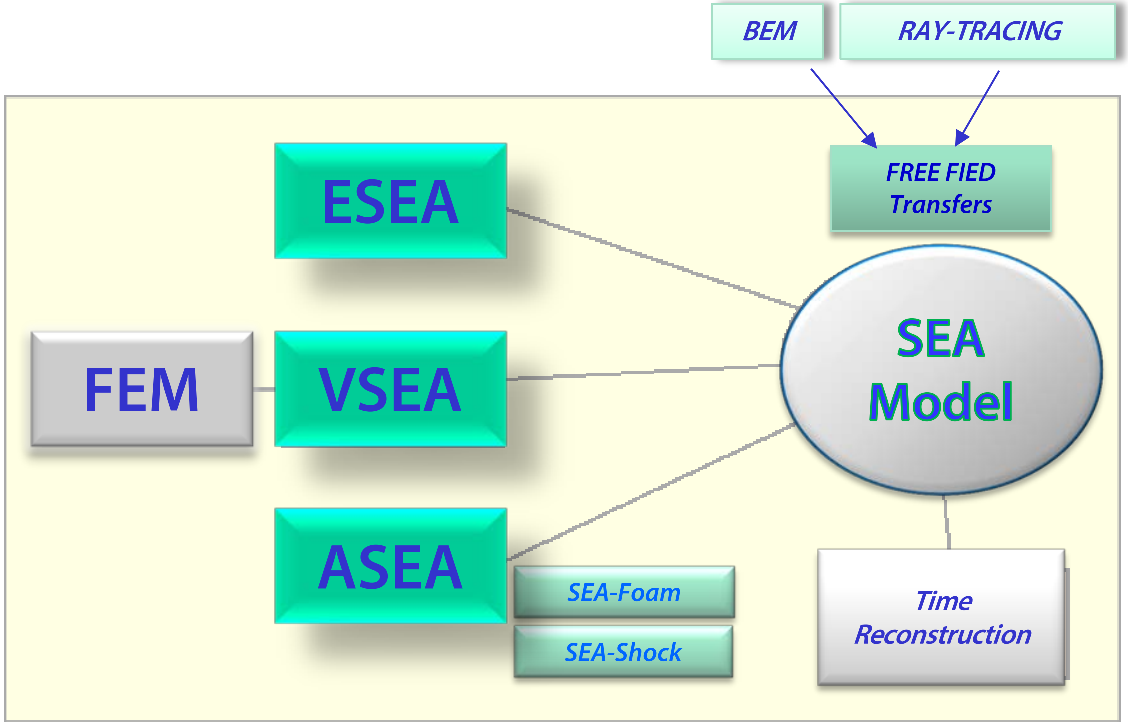




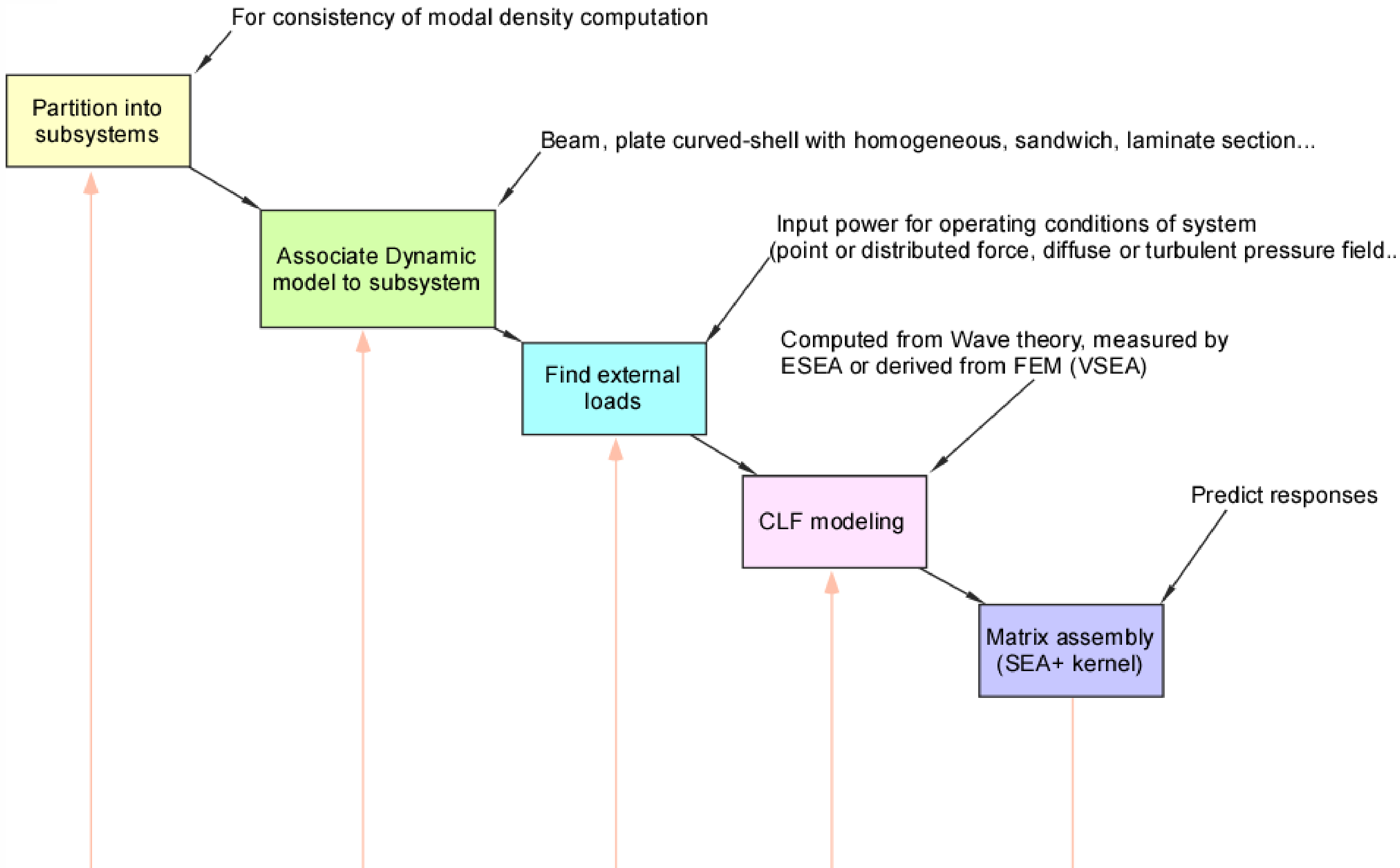


SEA+ Numerical Strategy

- Solve vibrational transfers in the energy domain using a statistical method (SEA) based on mixed VSEA-analytical formulations eventually hybridized with test data
  - Analytical SEA (**ASEA**) modeling of energy transfers (ASEA model)
  - Mixing VSEA and ASEA in the same network to get control from mid to high-frequency
  - Mixing free-field acoustic propagation problems and SEA models
  - Add constraints between subsystems

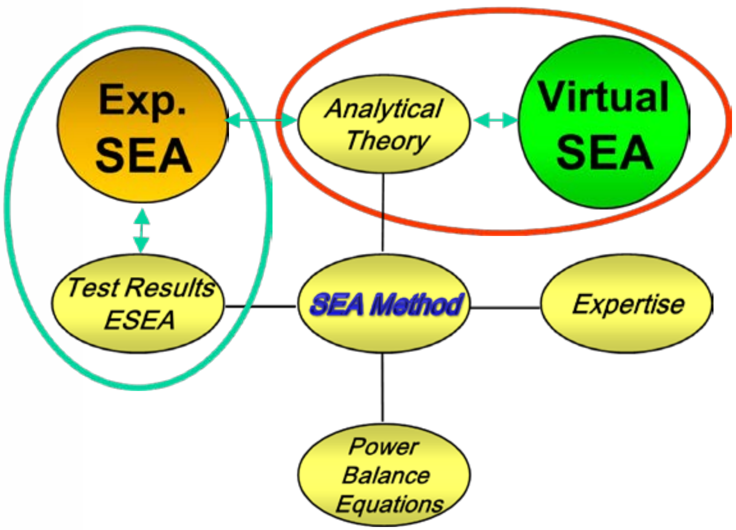


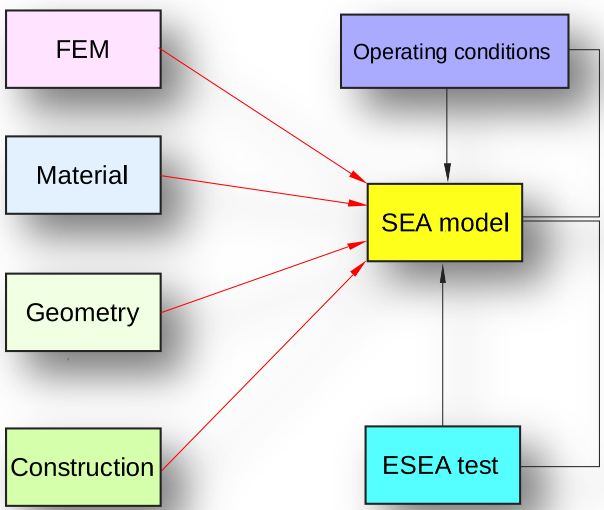
Steps in SEA analysis



Validation strategy of industrial SEA models

- SEA models may be view as "SYSTEM LEVEL" models as all model parameters may be hybridized with external data
  - Test and in particular ESEA are performed to control the physics or to provide measured SEA parameters such damping of coupling loss factors (DLF and CLF)
  - Previous phase is necessary when no expertise is available on the system and also before relying on SEA model in optimization analysis
  - VSEA is now used as a kind of virtual ESEA test and provides CLF, modal densities and wavenumbers to be compared to related analytical models

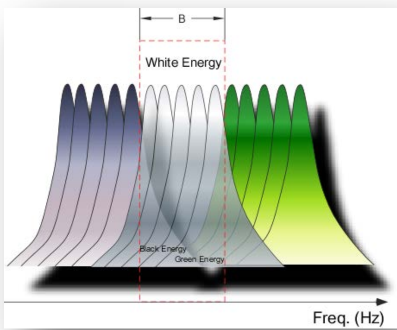


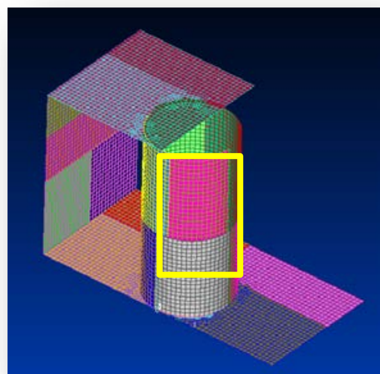


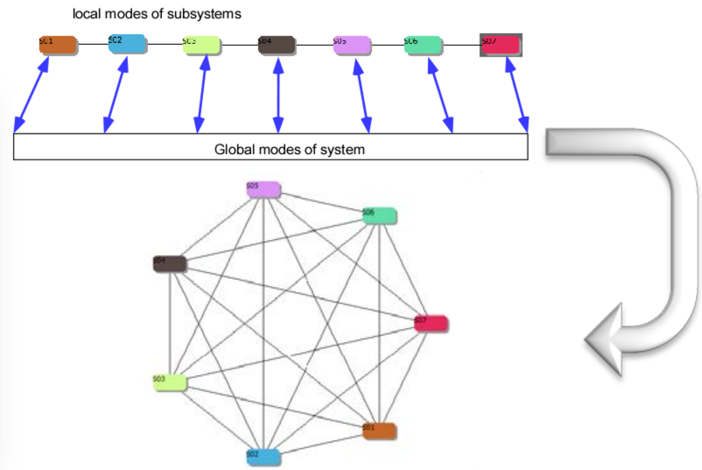
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Why measuring or using FEM in SEA modeling?

- SEA "classical" theory assumes "weak coupling" between subsystems
- From this, modal dynamic of the system is truncated in two ways
  - In frequency domain: modal density only accounts for resonant energy
  - In wavenumber domain (SEA partitioning) as global modes with large wavelength are removed from calculation







Frequency truncation implies neglecting non-resonant vibratory energy of local

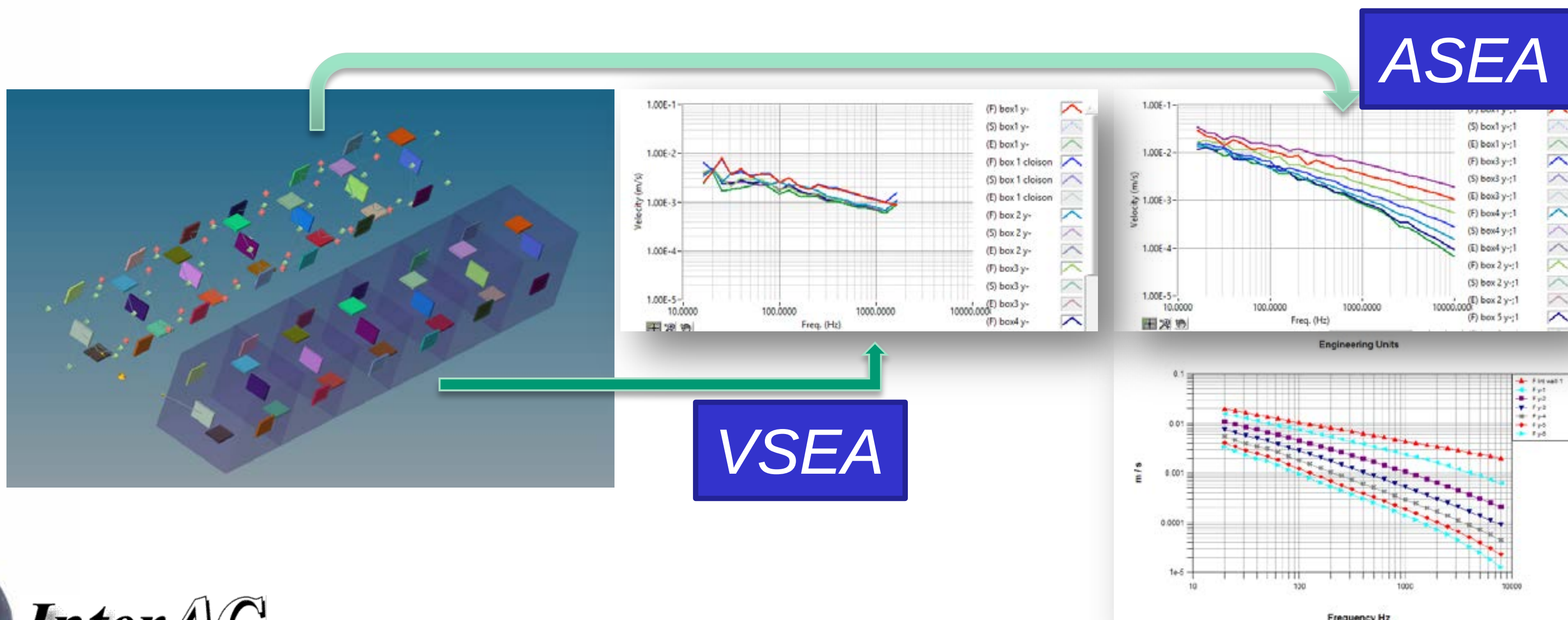
Spatial truncation, neglecting non-resonant energy from global modes i.e. to remove parallel coupling between subsystems.

In "classical" SEA some energy is therefore always missing and is called "Black" energy

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Why measuring or using FEM in SEA modeling?

- Black energy is mainly originated by kinetic energy transfers
- Black energy is often dominant in fluid/structure interaction in low and mid-frequency range
- It may be significant in long distance structure/structure transfers
- Support for Black energy prediction is implemented in SEA+ to overcome frequency band truncation
- VSEA predicts and ESEA measures indirect coupling between subsystems, manifestation of black energy transfers in the SEA network (domain truncation)



Overview of VSEA technique

- VSEA is a numerical process to compress the dynamics of FEM models into a small SEA loss matrix (VSEA model). This matrix can predict the transfer energy between subsystems with the quality of FEM model
- The transfer energy is estimated by starting from modal synthesis of global modes, followed by energy matrix auto-partition modal synthesis to end-up by SEA loss matrix delivery estimated by inverse SEA method. The process does not require any constraint on FEM and is fully automated. Virtual subsystems are then expanded by SEA+ analytical library to be run above the frequency limit of the FEM mesh

Virtual SEA: mid-frequency structure-borne noise modeling based on Finite Element Analysis G. Borello (InterAC), L. Gagliardini (PSA), L. Houillon (PSA), L. Petrinelli (Geci Systems), SAE Noise and Vibration Conference – May 6-8, 2003 – Traverse City, Michigan, USA
Virtual SEA: towards an industrial process, G. Borello (InterAC), L. Gagliardini (PSA), D. Thenail (PSA), SAE Noise and Vibration Conference – May 15-17, 2007 – Saint Charles, Ill, USA

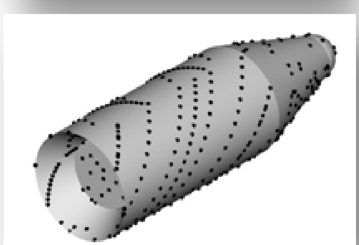
Band integrated FRF matrix generation when exciting FEM model with random point-forces on a grid of reference nodes

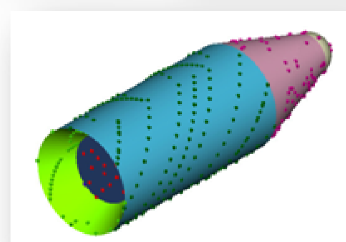
Auto-substructuration

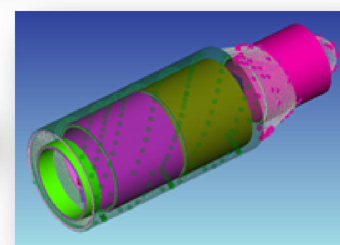
Grouping nodes to create subsystems

Compression into Mean FRF/subsystem matrix

Inverse technique to identify SEA parameters







SEA applications for aerospace

SPACE

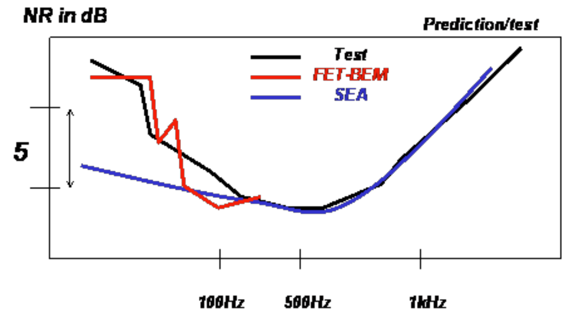
- Prediction of response to acoustic excitation of fairing, spacecraft
  - Vibratory response in reverberant chamber test
  - Vibratory response at rocket lift-off and transonic phase
- Prediction of random vibrations
  - Vibratory response of shaker tests
  - Random vibration at lift-off
- Prediction of separation shocks responses (pyro-cut, clampband)
  - Frequency response, time history and SRS to shock vents
- Prediction of microgravity in-orbit environment
  - Band-integrated and narrow band responses to peak harmonic excitation of control-attitude wheels, cryo-coolers, step-motors…

AIRCRAFT

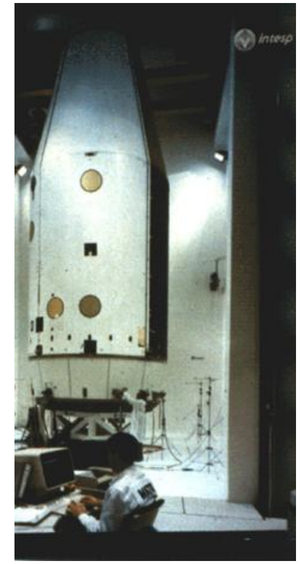
- Acoustic Transmission Loss of fuselage and noise in cabin prediction
- Prediction of in-flight levels from ground tests or simulation

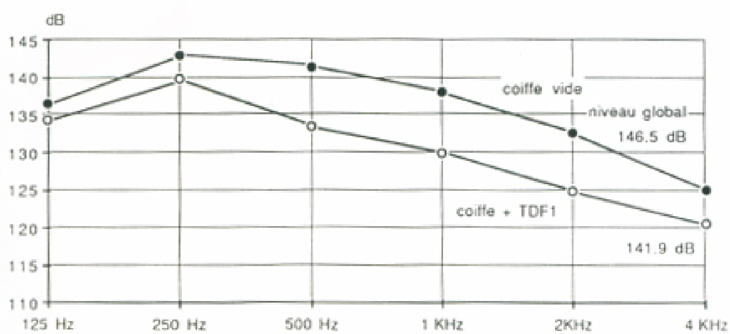
Earliest prediction of random vibrations due to acoustic loads in Ariane program

- **Ariane 4 & 5 (1984-1990)**
  - Under-fairing noise prediction
  - Equipment bay acoustic random response
- **Payload characterization**
  - Absorption measurement
  - Fairing/Payload coupled analysis
- **Payload SEA random response prediction**
  - With Aerospatiale LASCAR software

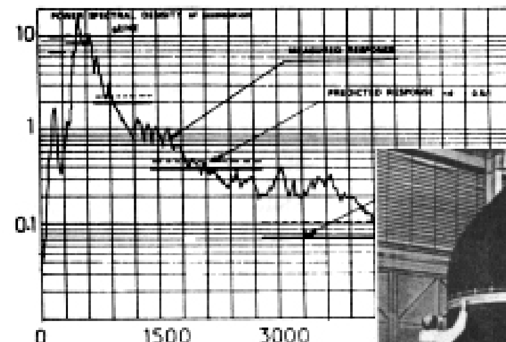


Index of noise reduction of the Ariane 4 fairing undertaken acoustic test in reverberant room

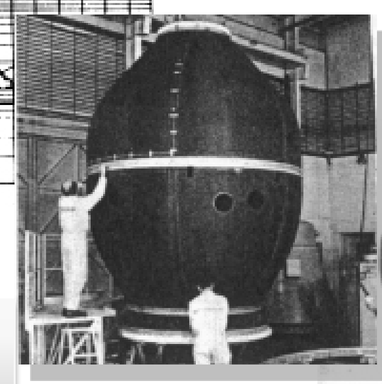


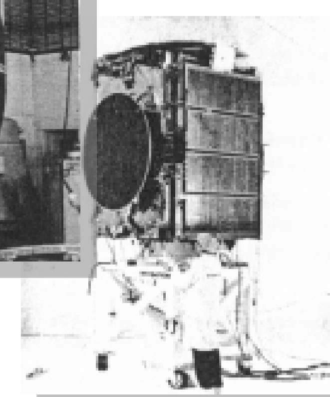


Noise under empty fairing and predicted internal fairing noise with payload aaaaaaaaaabsorption (TDF1 measured absorption)



Acceleration on the cylindrical part of the SYLDA structure (measured narrow band, prediction octave)- AEROSPATIALE

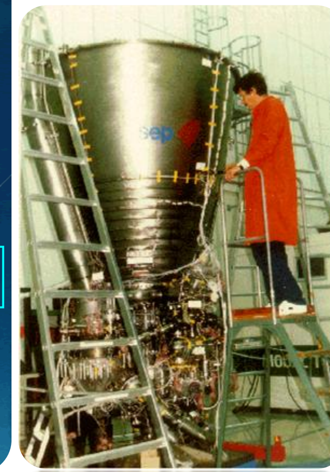


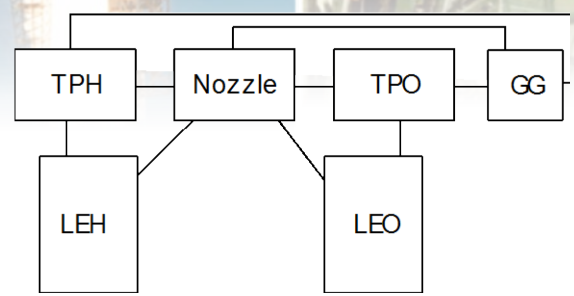


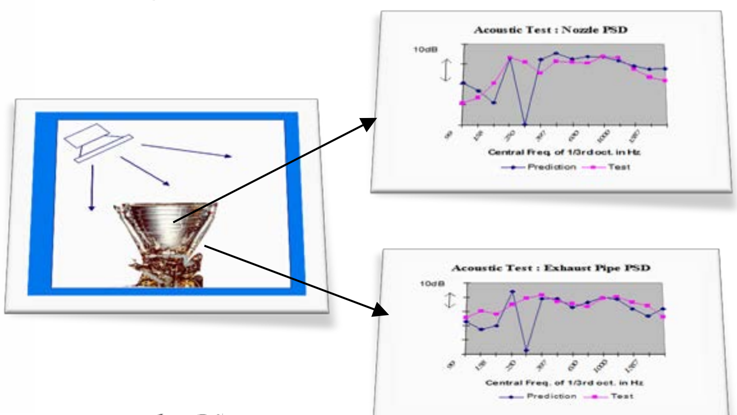
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Acoustic qualification of Ariane VULCAIN engine (Prediction of random vibrations due to acoustic loads)

- **Acoustic qualification of VULCAIN engine (1991-1995)**
  - Experimental SEA testing of VULCAIN
  - Hybrid SEA modeling for predicting broad band acoustic vibrations using dedicated SEA software
  - Validation on acoustic test in reverberant Room
  - Modification of VULCAIN test bench to increase noise levels from jet plume on VULCAIN when firing
  - Prediction of modified test bench environment and in-flight levels prediction using SEA





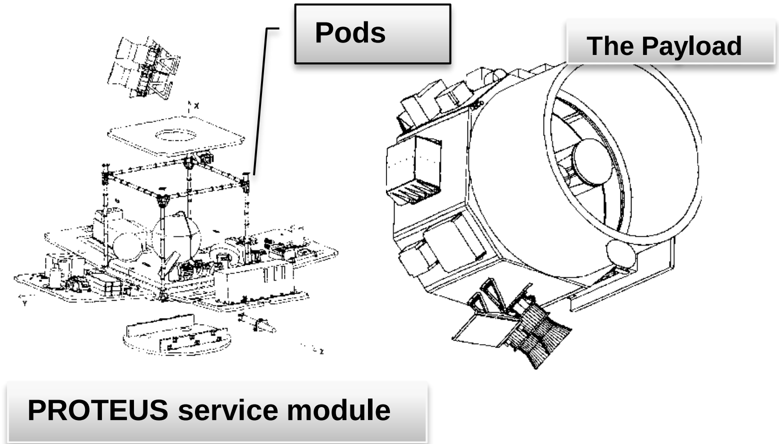


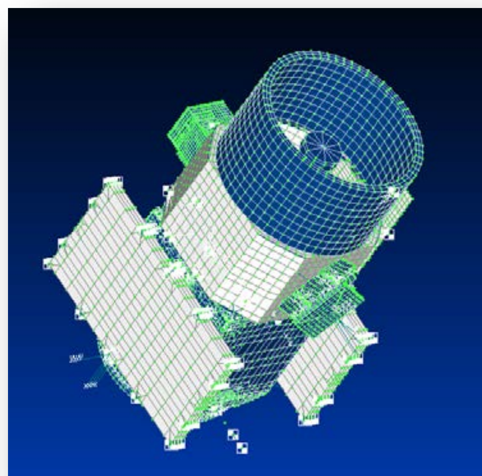
On left Validation of VULCAIN SEA model (above) obtained by comparing the digital simulation of the acoustic test in reverberant chamber with measurement results (test in pink, calculation in blue)

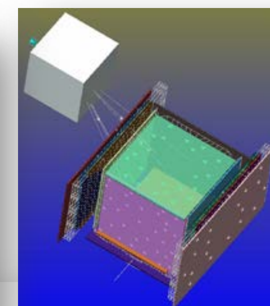
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

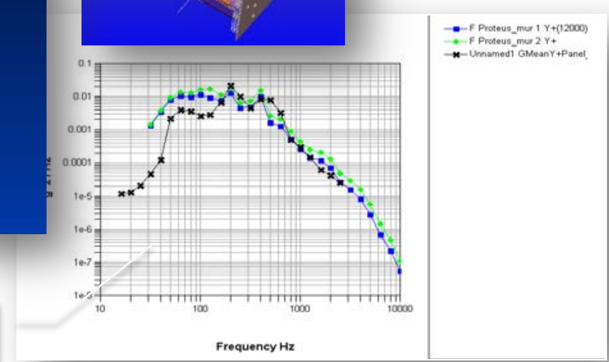
Risk Analysis of Calipso submitted to acoustic loads (Prediction of random vibrations due to acoustic loads)

- SEA modeling for reducing test cost
  - Prediction of acoustic response of CALIPSO spacecraft and validation
  - SEA proved payload might be tested separately from service module









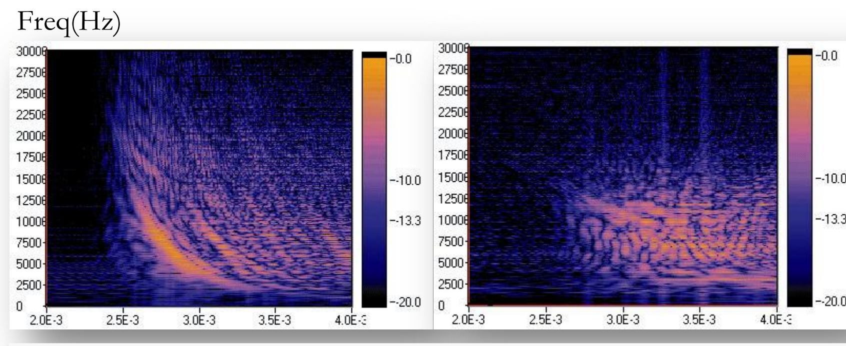
Comparison of mean geometrical average of four available test data on Proteus wall Y+ with related SEA prediction on the two SEA sub-panels that represent Y+Wall (reverberant chamber PROTEUS alone test)

Mean PSD from test data

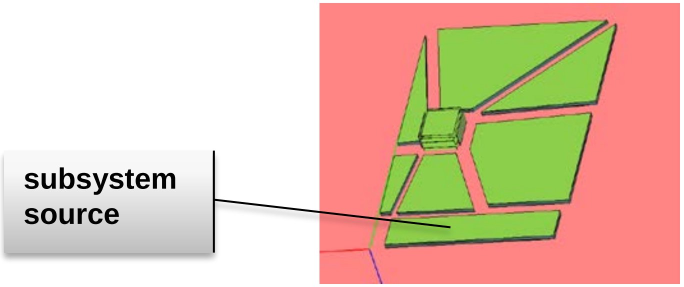
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

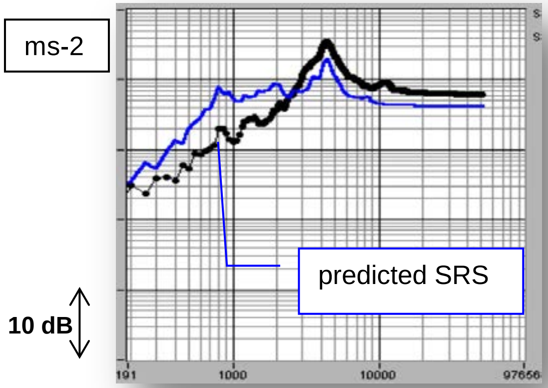
Earliest shock prediction using LMPR shock reconstruction
(Response of equipment to shock loads)

- **Far from shock source, energy is diffusing-> SEA is applicable**
- **SEA modeling to predict shock**
  - Through CNES R&D, development of LMPR algorithm to add local-mode phase to SEA FRF and invert them in time domain
  - From time history source term, time history are obtained from system level SEA model
- **Validation**
  - Test of the method on plates with shaker, hammer impact, pyrosources



Evolution of Frequency (Y-axis) vs. Time (X-axis) of two pyroshocks test acceleration signals, synchronously recorded at two different locations
(left) on aluminum base plate supporting equipment
(right) at a particular equipment foot point



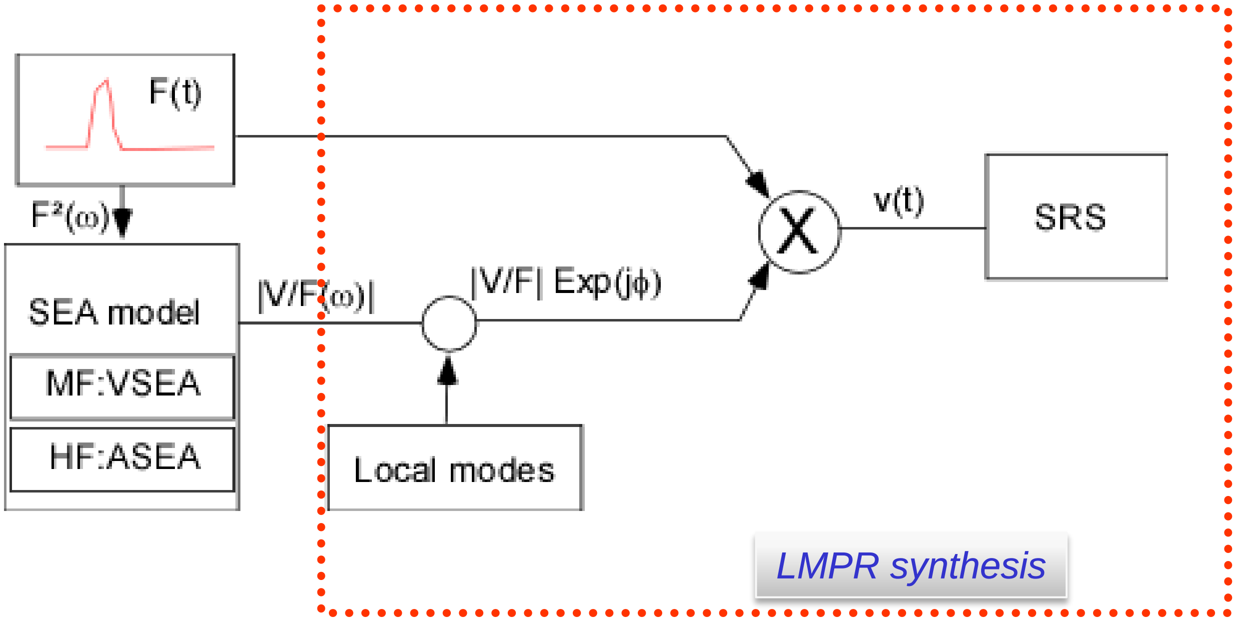


Comparison between SRS computed from test acceleration recorded on the equipment electronic card in MBDA pyroshock test and SRS predicted using LMPR

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

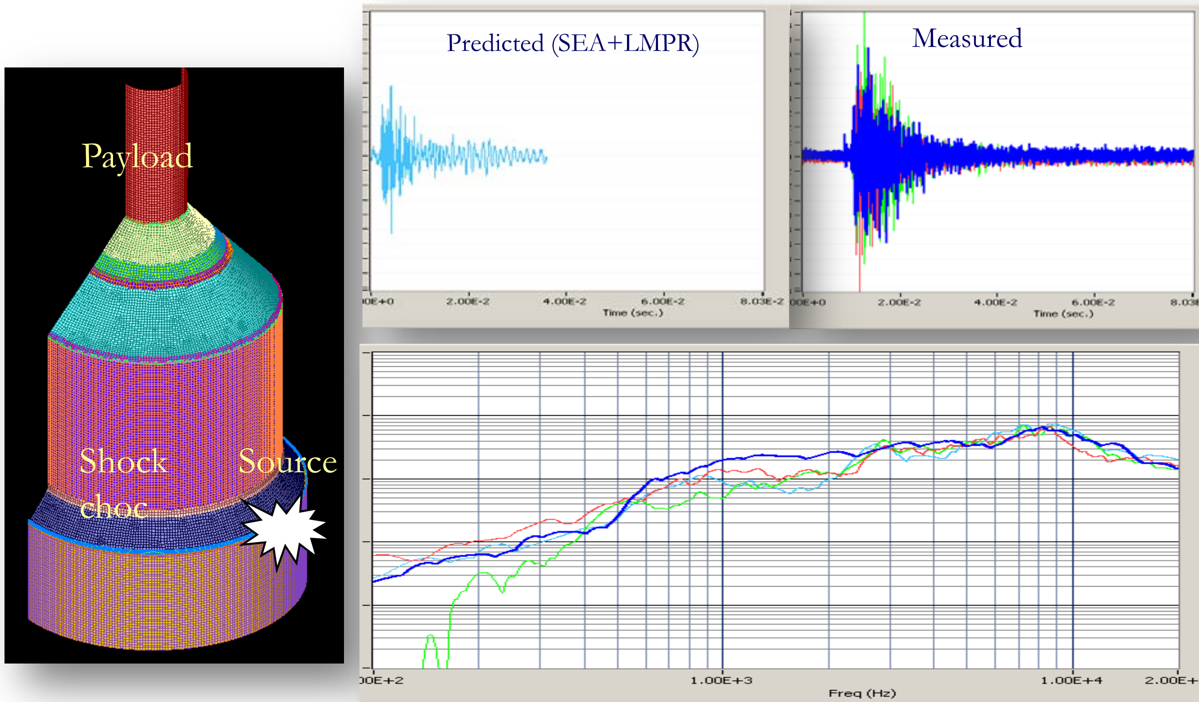
LMPR solve for shock synthesis

- LMPR modal synthesis for time reconstruction in receiver subsystem
  - Use analytical modes for thin and sandwich subsystems
  - Use pseudo-mode computed from wave-number and mode count for others
- Computation of SRS (COX algorithm)



Prediction of Shock response spectrum due to shock loads

- Application of LMPR to Ariane 5 upper part (2003)
  - Fairing separation test simulation

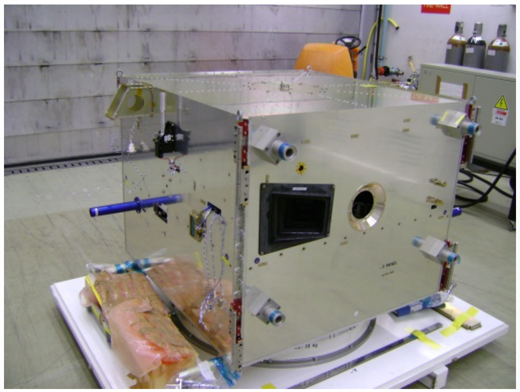


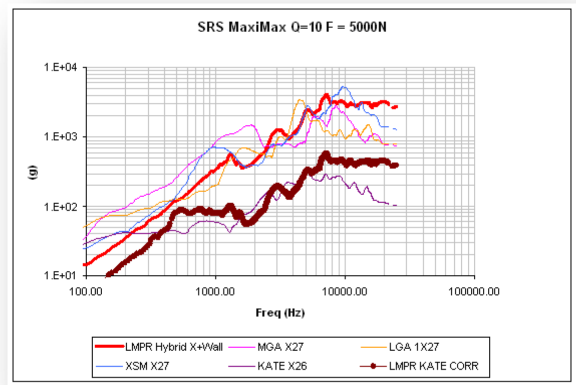
Forecast of shock response spectra of the payload during separation from the ARIANE 5 fairing. Left, view of the upper ARIANE 5 part FEM model in double launch configuration; Right top, average time response of the payload predicted using SEA model and LMPR algorithm; from top to bottom, the related Shock Response Spectra (predicted SRS in blue; Measured SRS in various points of the payload-launcher interface other colors)

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

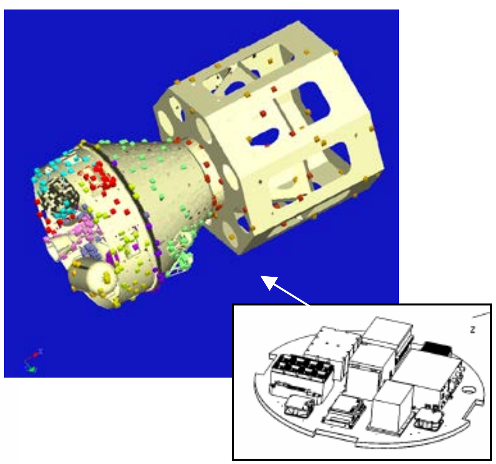
Prediction of Shock response spectrum due to shock loads with dedicated software

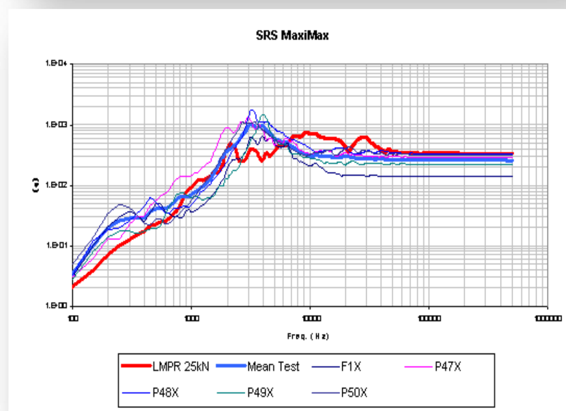
- Application of LMPR to payloads using SEA-Shock software (ESA-2007)
  - Prediction of SMART1 clampband and pyroshock test
  - Prediction of VEGA upper part clampband and pyroshock test





X+Wall SRS predicted by LMPR (in thick red with bare panel velocity and thick brown for mass corrected bare velocity) and SRS computed from SHOGUN measured responses





SRS prediction (red and blue)/tests results on equipment platform for AVUM stage separation for VEGA system

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Micro gravity environment control and prediction

- Define an integrated analysis and test methodology for generation and propagation of micro-vibrations in observation satellites.
- Define associated experimental characterization techniques.
- Main issues:
  - Identify the perturbation sources
  - Estimate their disturbance levels
  - Characterize the modal behavior of the spacecraft structure by tests and/or predictions
  - Deal with the interaction when a spectral ray of the disturbance coincides with a structure mode
  - Assess a pointing budget at the equipment level

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

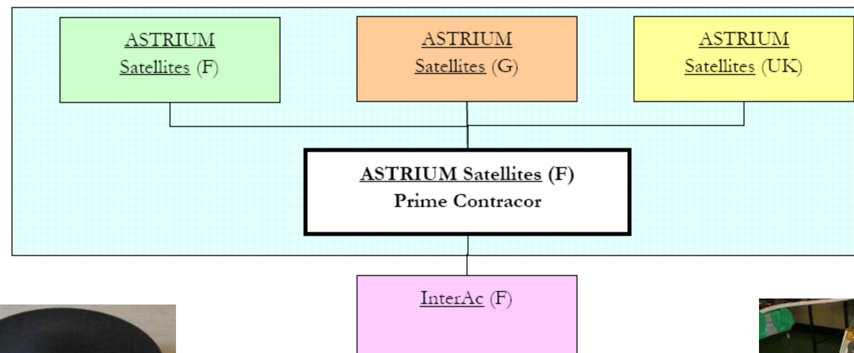
3 sources / 2 approaches

FEM approach
Study at LF/MF (<500Hz)

Reaction wheel

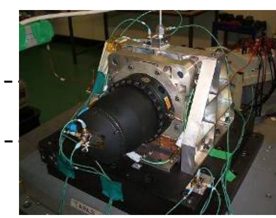
Pointing mechanisms with stepper motor

Cryo-cooler compressors



Energy approach
Study at MF/HF

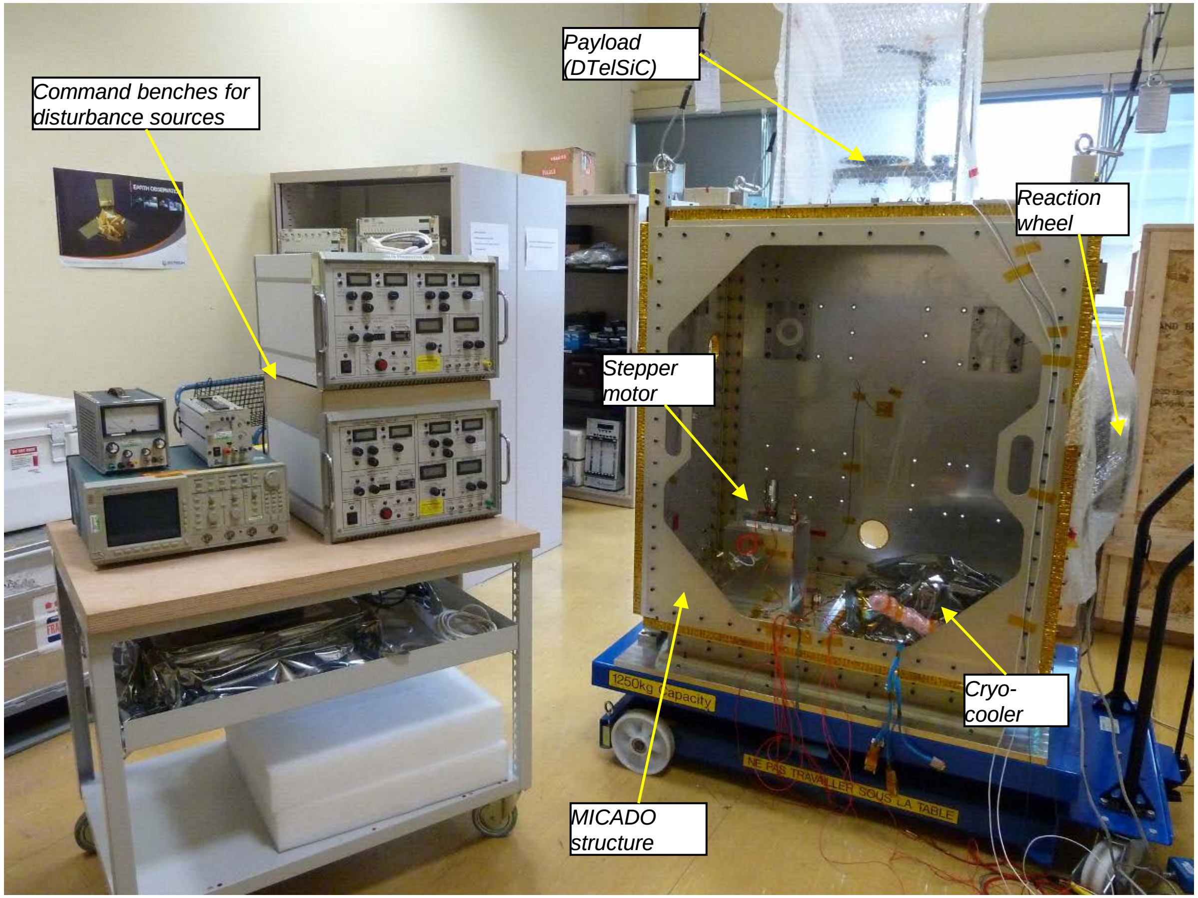
Reaction wheel



Cryo-cooler compressors

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Overview of the ASTRIUM test configuration



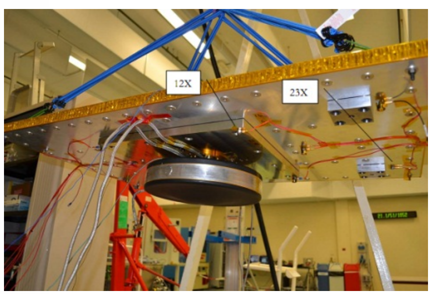
Test facilities handling tools

Closer view to SiC payload

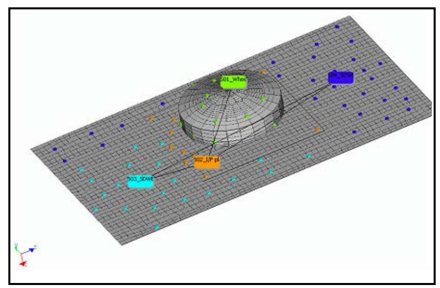
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

SEA numerical strategy

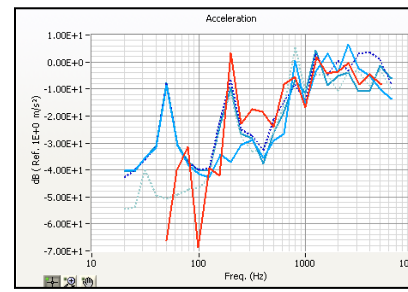
- Deriving SEA model from FEM using the **Virtual SEA** (**VSEA**) technique
- Validating SEA transfers against FEM transfers and **Experimental SEA** test (**ESEA**)
- Analyzing
  - MICADO panel under source excitations
    - Reaction wheel excitation in steady and unsteady states
    - Cryo-cooler excitation in various operating modes
  - MICADO payload with several operating sources
- Comparing SEA prediction against operating condition tests



Dedicated test based on ESEA is performed on a structure panel equipped with a wheel to characterize energy transfers in MF-HF range



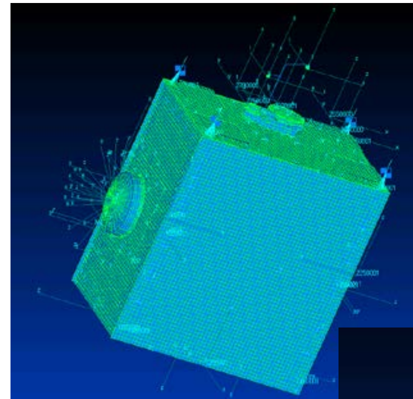
VSEA model generation by auto sub-structuring and validation against ESEA

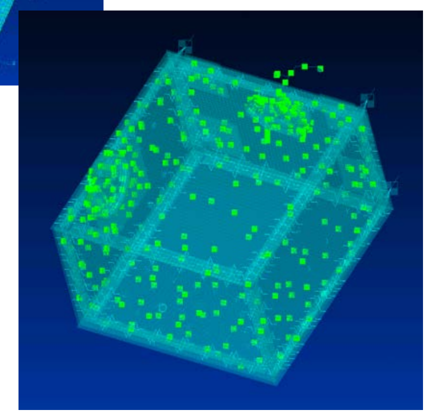


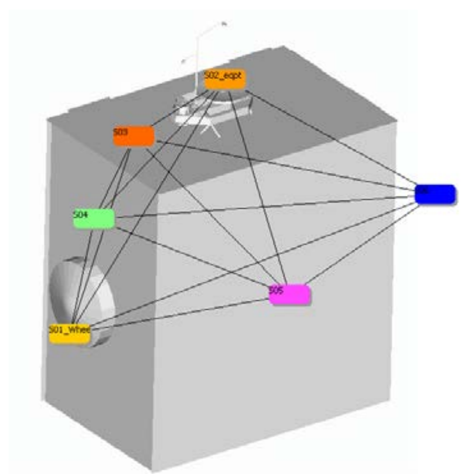
VSEA prediction (red curve) against measurements performed with operating wheel

MICADO VSEA Modeling

- Starting from MICADO FEM from Astrium
  - Wheel
  - Receiver equipment
- Applying VSEA analysis
  - Six identified subsystems
  - Model limit: 4 kHz
  - Assumed 1% default DLF

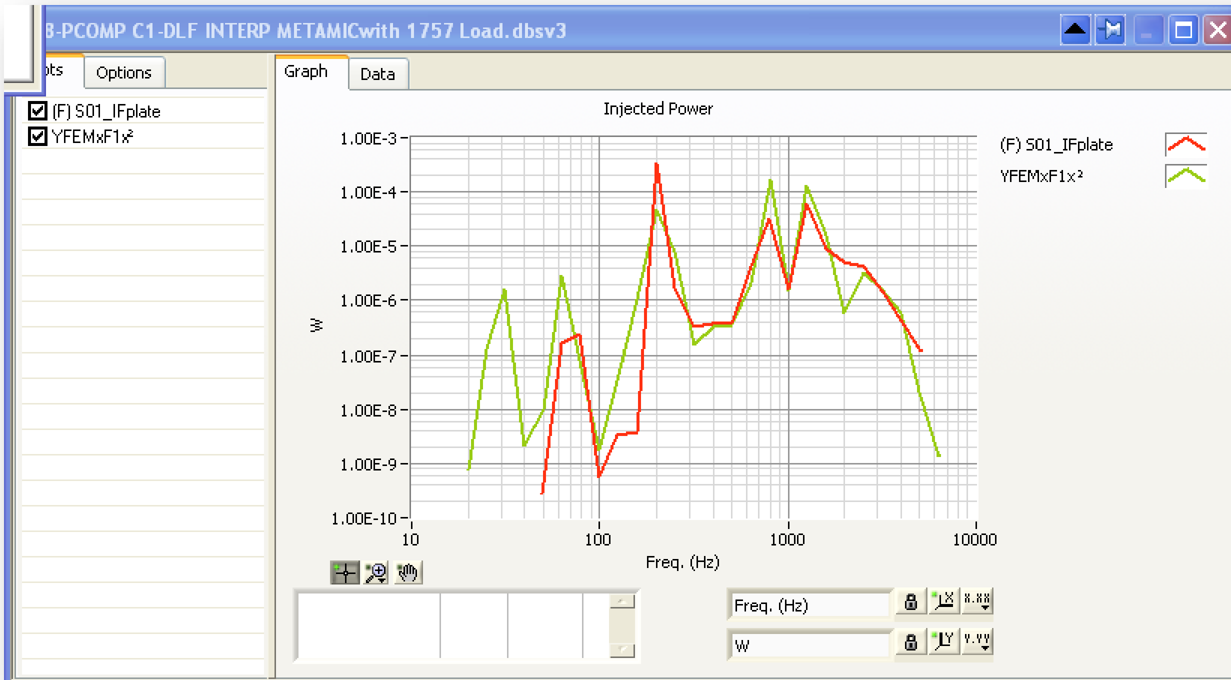






Improving 3D field reconstruction and confidence level with narrow band sources

- Calculation of injected power in 1/3rd octave: $P_{inj} = \langle Y \rangle \cdot \left| F(f_c, \Delta f \right|^2$
- With narrow band loads: $P_{inj} = \int_{\Delta f} \mathrm{Re}\{Y(f,M)\} \cdot \left| F(f) \right|^2 df$

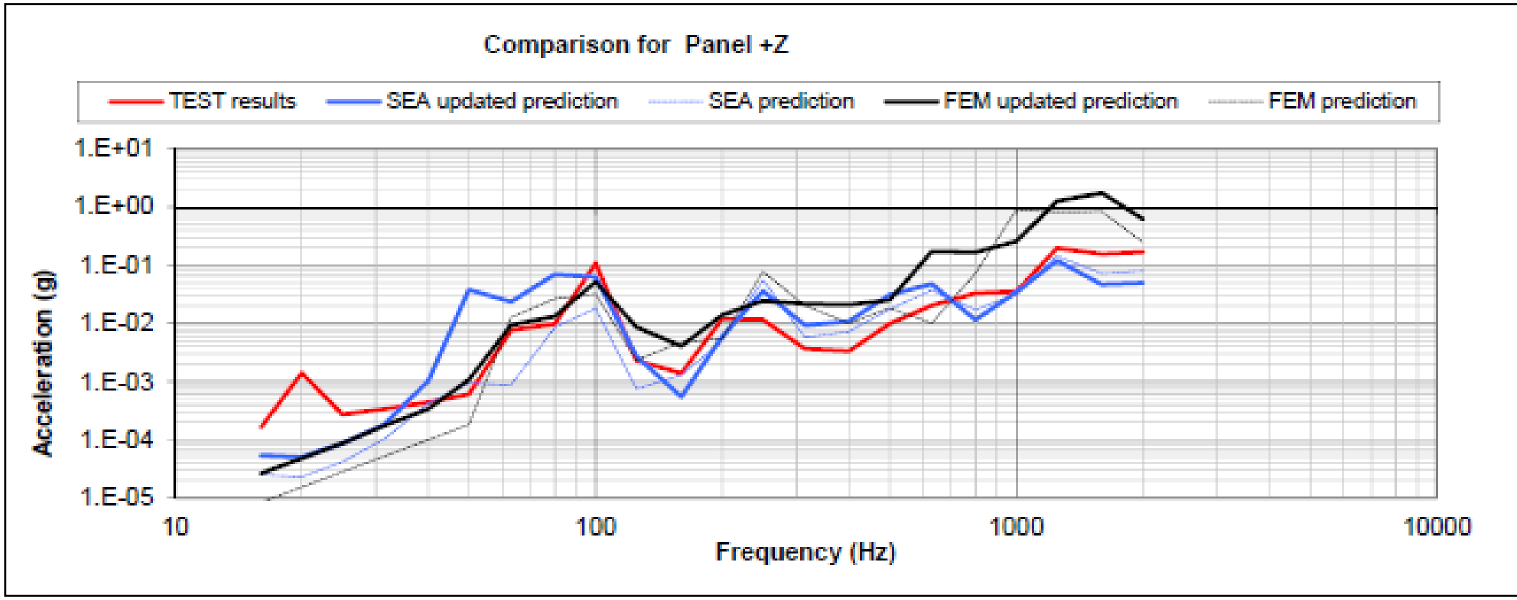


Band-integrated injected power* YFEM * F² *computed from narrow band and band-integrated power from band-averaged mobility and band-integrated force

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

SEA versus FEM (sweep wheel rate)

- The SEA prediction shows a better correlation than the FEM prediction starting from 100Hz.



  - Updated Virtual SEA model w.r.t. updated MICADO FEM.
  - VSEA model loaded by the injected power based on force introduction computed from an average (and corrected) load measured at wheel interface.

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Analysis of sound transmission in Aircrafts

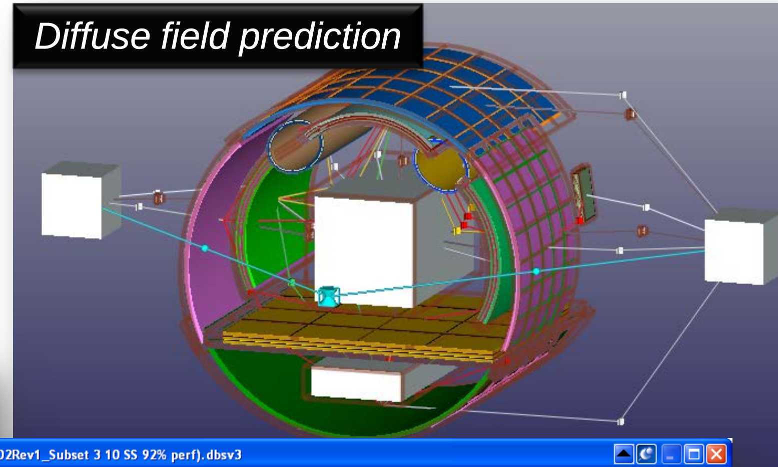
- Prediction of acoustic transparency of fuselage and performance analysis of
  - acoustic blanket,
  - Mechanical insulation through shock mounts
  - Sound Radiation of complex ribbed composite curved shells
- Predicting in-flight vibroacoustic environment from ground tests
  - Preparing experimental SEA test with the help of Virtual SEA analysis (determine number and extent of subsystems with best transducer location)
  - Measuring SEA parameters of aircraft cockpit under calibrated excitation (impact hammer and loud-speaker)
  - Build hybrid SEA model to predict in-flight environment

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

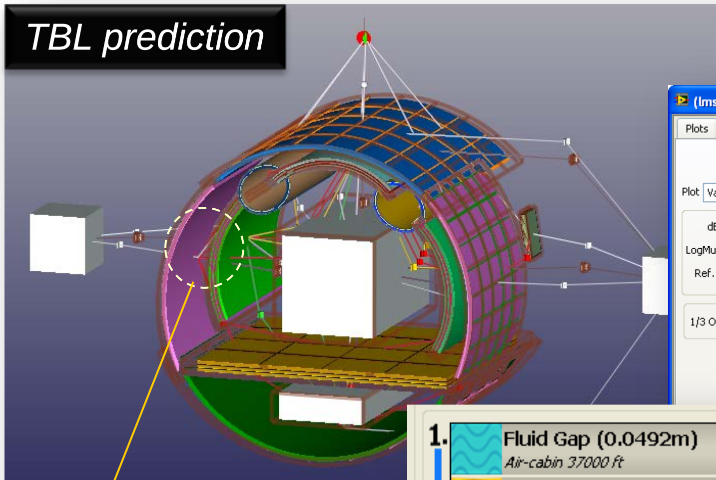
Aircraft Internal Noise Prediction

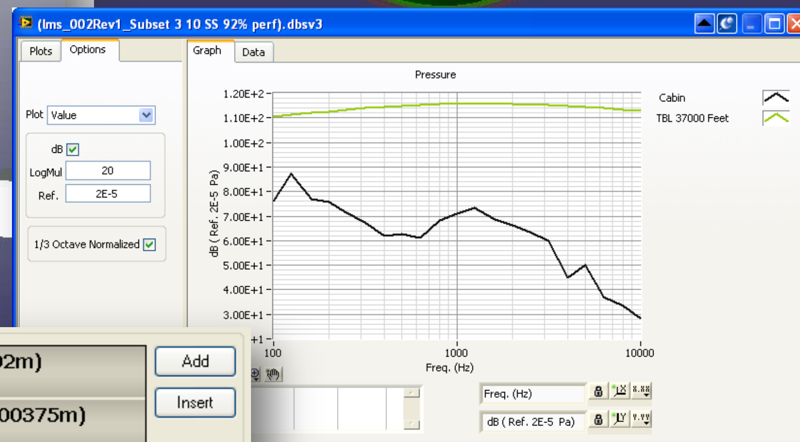
- Prediction of sound transmission in aircraft fuselage
  - Attachment of internal liner is achieved by multipoint junction with decoupler impedance insertion
  - f > 1000 Hz ASEA model
  - f < 1000 Hz VSEA model

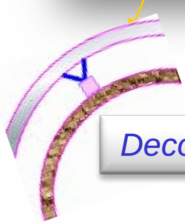
Diffuse field prediction



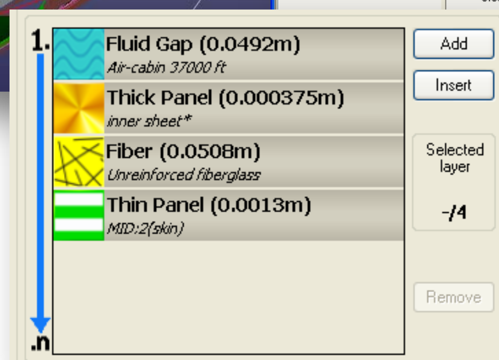
TBL prediction







Decoupler modeling

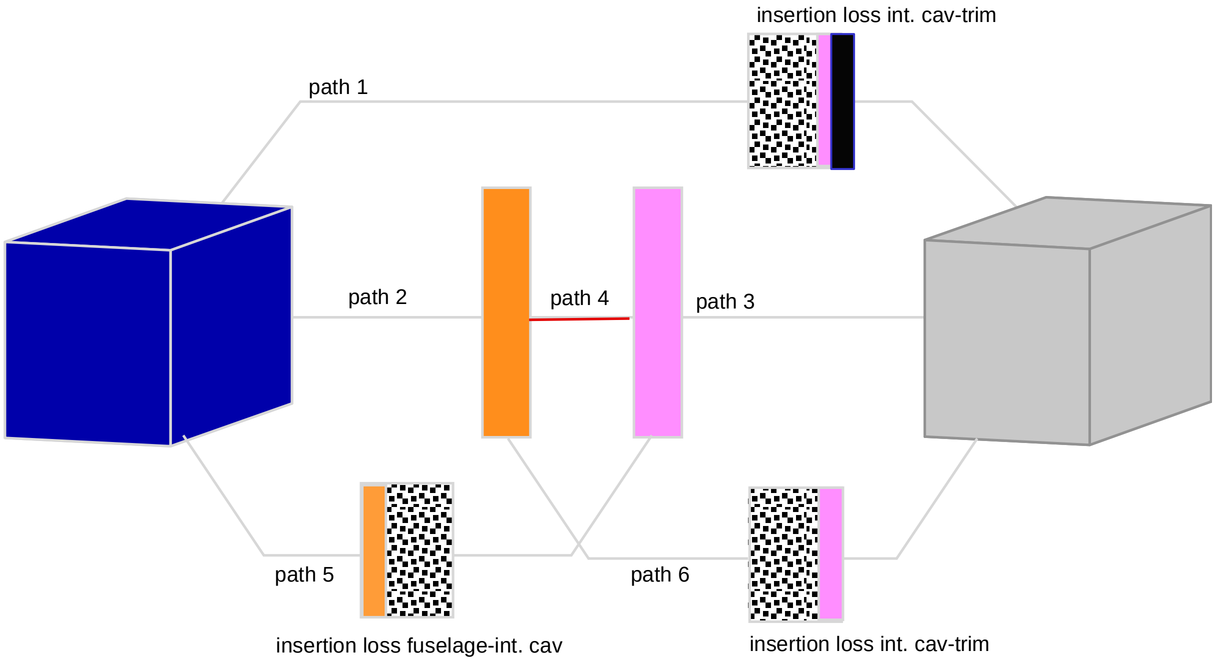


Acoustic trim modeling

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

SEA modeling scheme for predicting acoustic transmission through a trimmed structure

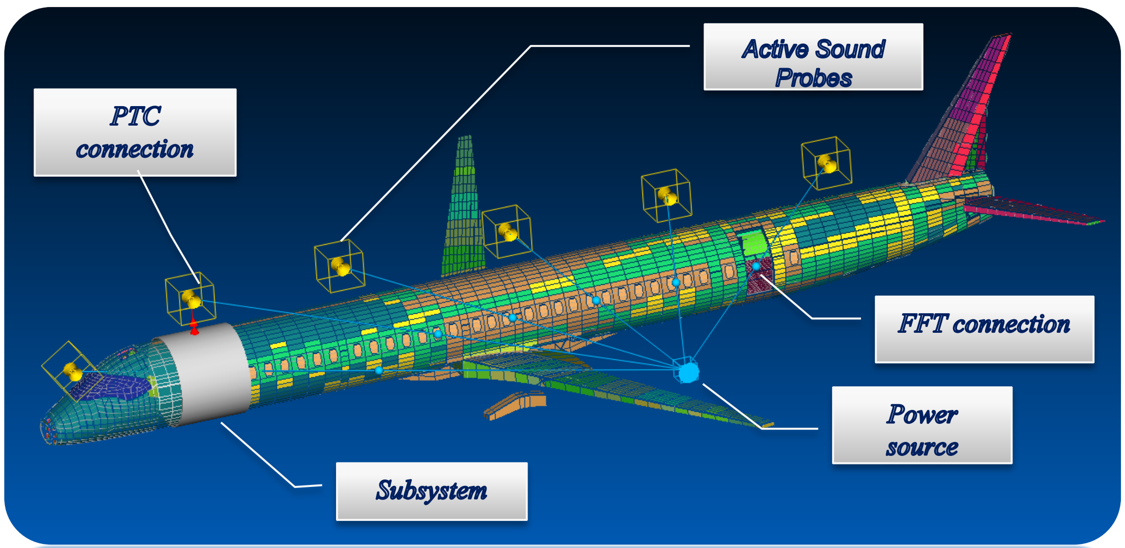
- SEA power flow is used to rank the various paths in the system



$$P_{ij} = \omega\left[\eta_{ij} E_i - \eta_{ji} E_j\right]$$

Active Sound Probes and FFT Connection

- Local pressure in far field is predicted with Active Sound Probe (**ASP**)
- ASP may connected to elements radiating power (sources, SEA cavity or structure) across FFT connectors which transfer power to the far field
- Local ASP pressure is re-injected in SEA subsystems through Power Transfer Connectors (**PTC**)
- ASP local pressure may be made locally diffuse or propagative (fixed incidence)



InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Summary of aerospace applications

- SEA expertise developed in Space programs and related to random acoustic vibrations, shock responses and micro-vibrations has been reviewed
  - Micro-vibration loads involve rotatory components and very peaky signals in the frequency domain, needing a narrow band approach for computing injected power from forces. SEA modeling provides more representative results than FEM above first modes of vibrations
- For aircraft, flight vibroacoustic levels are well predicted by linking SEA method with FEM complementary analysis and experimental SEA test (Virtual and experimental SEA methods)
- More generally SEA models are allowing engineers to capture the physics of the vibration they have to handle and from that to master it

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

SEA applications for automotive and building industries

AUTOMOTIVE APPLICATIONS

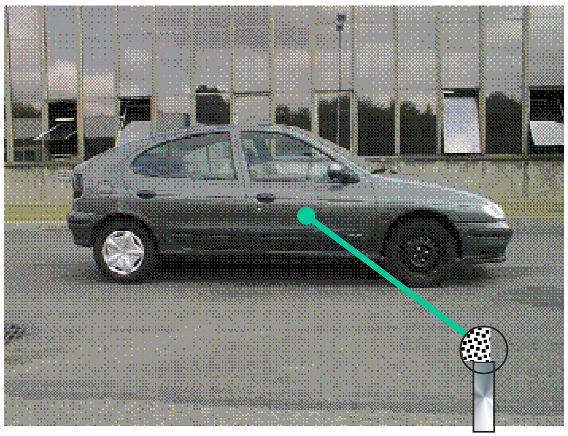
- Prediction of exterior radiated noise in running conditions
  - Noise reduction of by-pass noise using passive treatment
  - Modeling acoustic transfer paths from internal sources to exterior environment
- Prediction of internal noise in driver's cabin
  - Prediction of airborne paths
  - Prediction of structural borne paths
  - Optimization using passive solutions

BUILDING ACOUSTIC APPLICATIONS

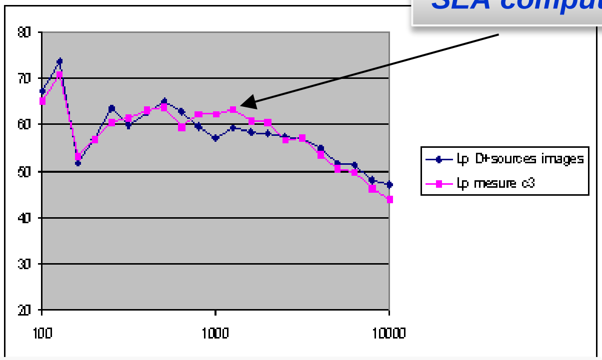
- Prediction of noise insulation in building
- Prediction of acoustic performance of components

Prediction of exterior noise radiation of cars

- Objective: prediction of noise radiation at a 7.5 m distance from vehicle (EC standard)
- SEA model goal: investigate effect of absorption materials on radiated pressure

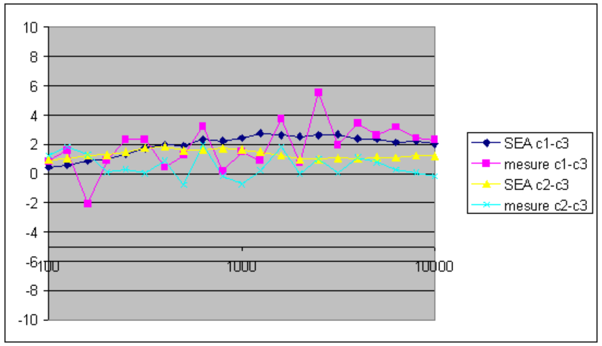


SPL prediction at 7.5 m



SEA computation

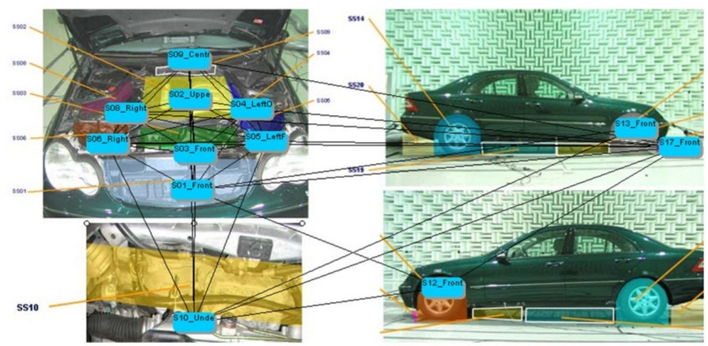
Absolute level prediction/measured

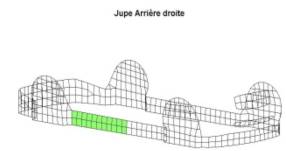


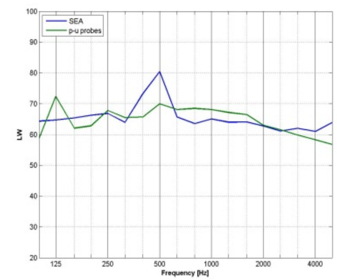
Relative Lp change from different configurations of trim panels (measured and computed)

Prediction of by-pass noise test (SONVERT research program)

- SEA model is built from ESEA test and then made analytical by introducing equivalent surface coupling area between internal cavity subsystems
- SEA predictions were as good as more complex methods (as soon internal cavities are weakly coupled f > 1000 Hz)

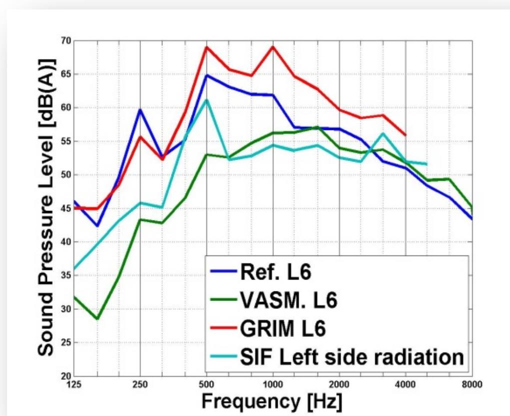


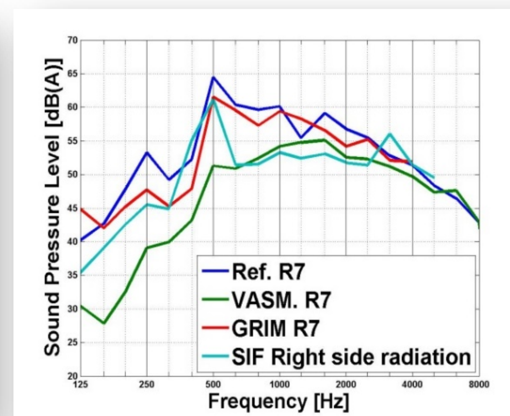




Example of radiated power prediction compared to direct measured power (intensity with microflown PU probes)

SPL at distance predicted by
- VASM
- GRIM
- SEA (SIF)

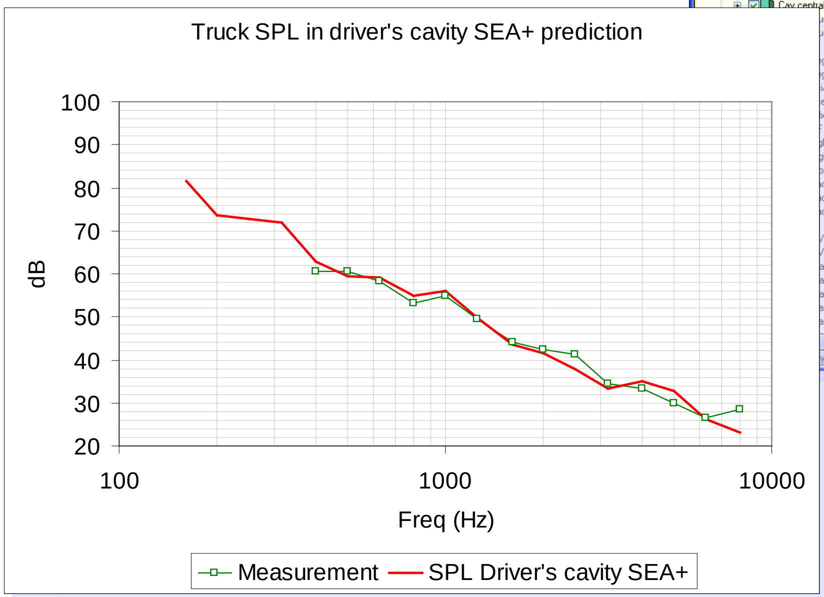


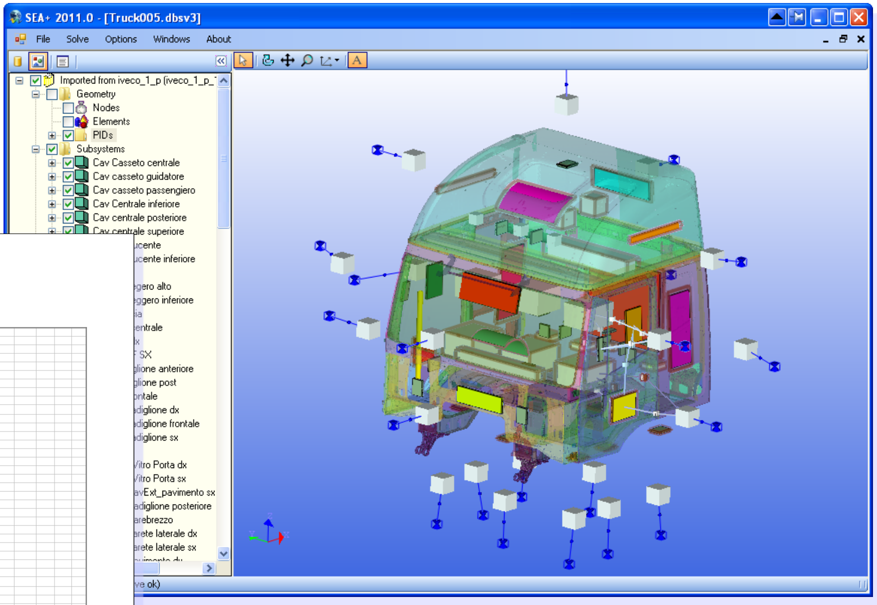


InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Noise in Truck Cabin

- **SEA+ model built on top of VSEA model**
  - VSEA-> 400 Hz and analytical extrapolation > 400 Hz
  - Doors modeled as double-wall with TMM
  - Diffuse acoustic loading

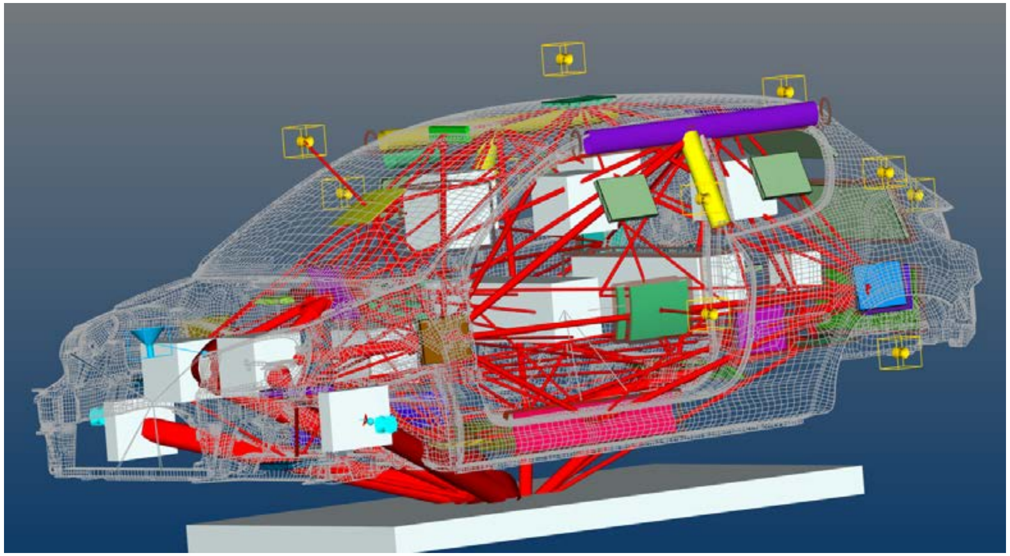




SEA+ truck cabin model

Sound optimization in cabin

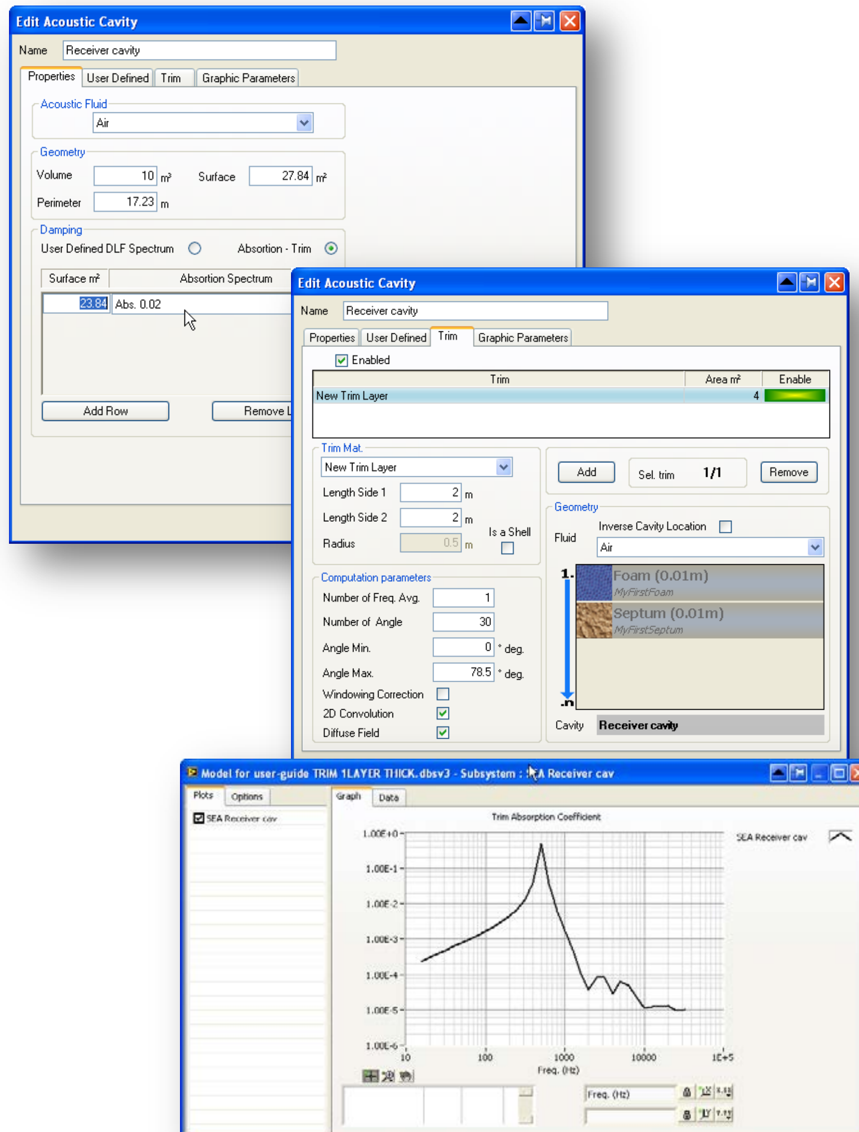
- SEA model of the car cabin must take into account all structures, acoustic volumes, trims and leaks involved in transmission of internal acoustic pressure
- Validation of SEA model is required to verify all predominant transmission paths are well represented in the analysis
- Optimization of acoustic trim packages is undertaken under constraints to reduce internal noise with minimal trim mass and cost



Predicting absorption from trims

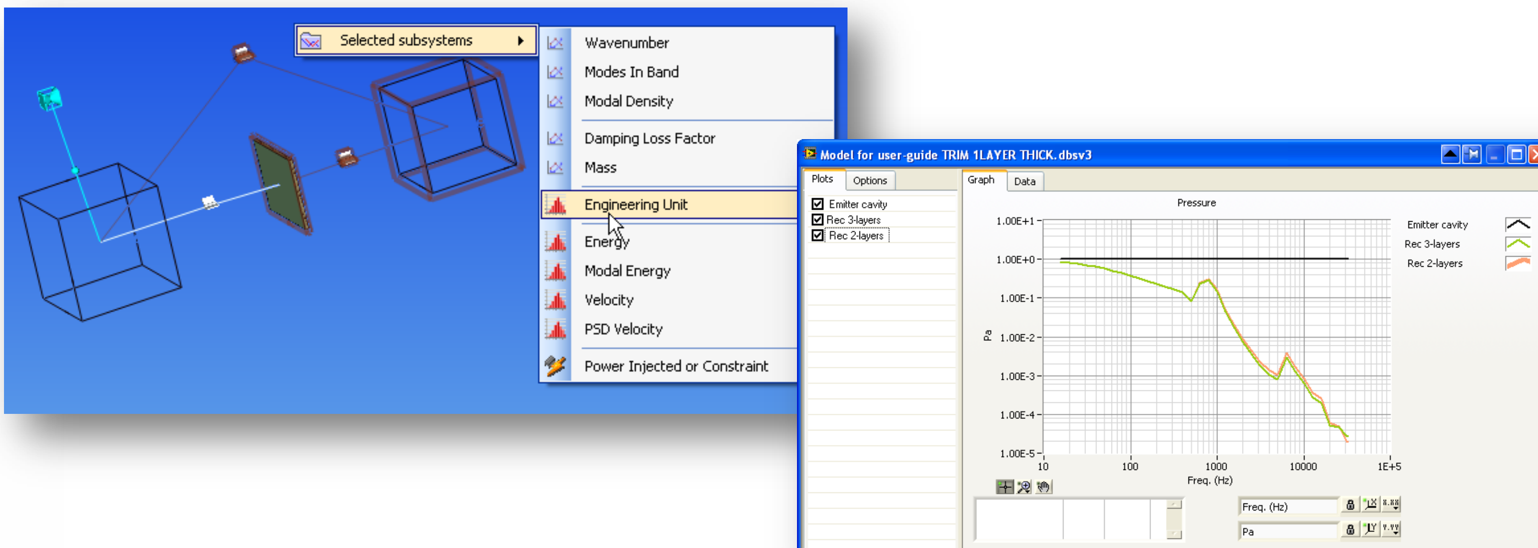
- The composite absorption is automatically calculated from bare wall absorption and from all trims added to the cavity

$$\alpha_{rec} = \frac{\sum_{i=1}^{i=N} \alpha_i^{trim} A_i^{trim} + \sum_{i=1}^{i=N} \alpha_i^{spectrum} A_i^{spectrum}}{A_{cav}^{tot}}$$



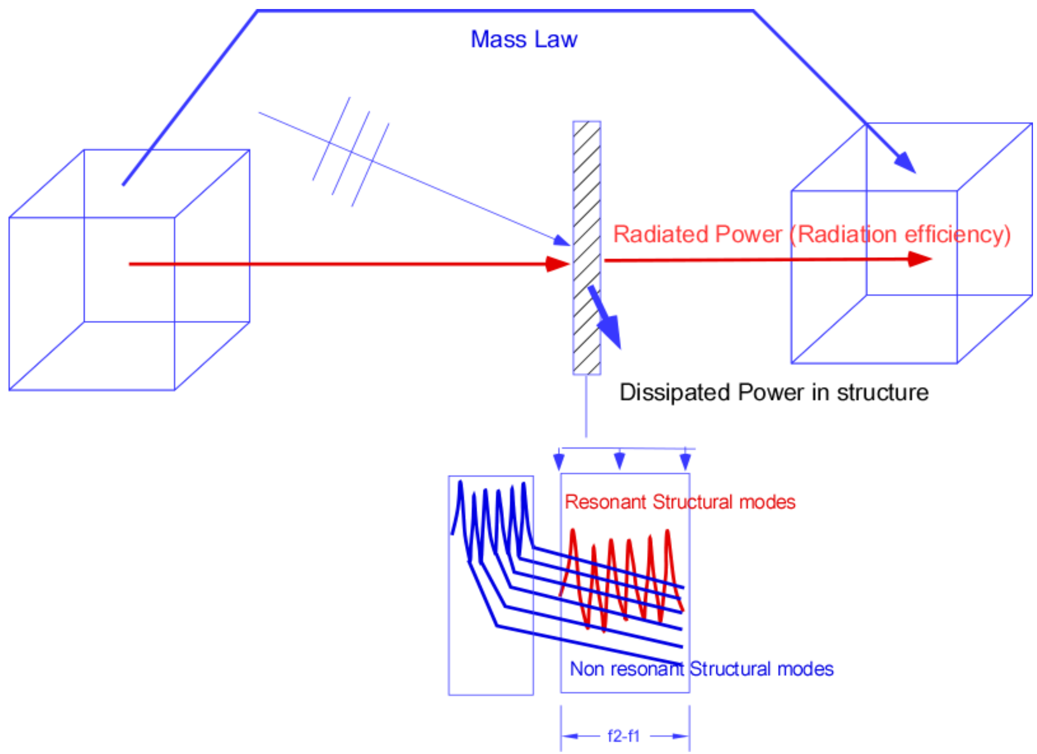
Predicting noise reduction

- The drop of pressure in coupled trimmed cavities is computed from the SEA+ model
- Practical applications: influence of trim characteristics & acoustic optimization



InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Power equilibrium in panel transmission



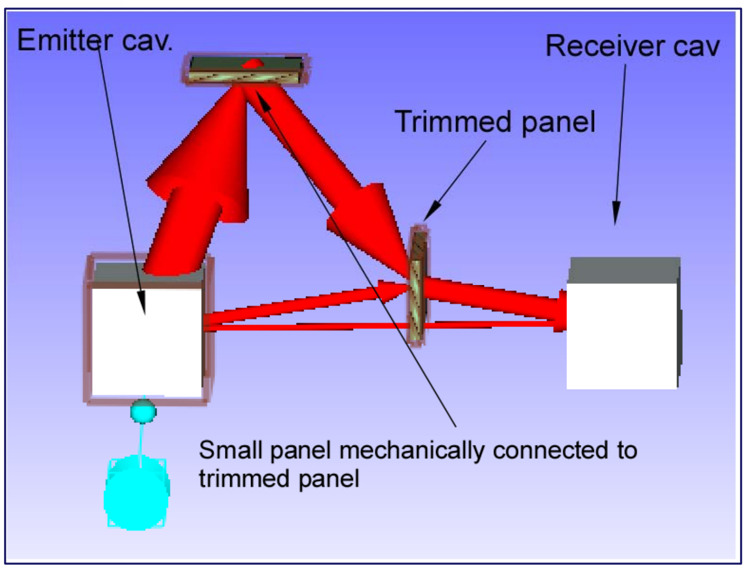
$$\omega \begin{bmatrix} (\eta_1 + \eta_{12} + \eta_{13}) & -\eta_{21} & -\eta_{31} \\ -\eta_{12} & (\eta_2 + \eta_{21} + \eta_{23}) & -\eta_{32} \\ -\eta_{13} & -\eta_{23} & (\eta_3 + \eta_{31} + \eta_{32}) \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} \Pi_1 \\ 0 \\ 0 \end{bmatrix}$$

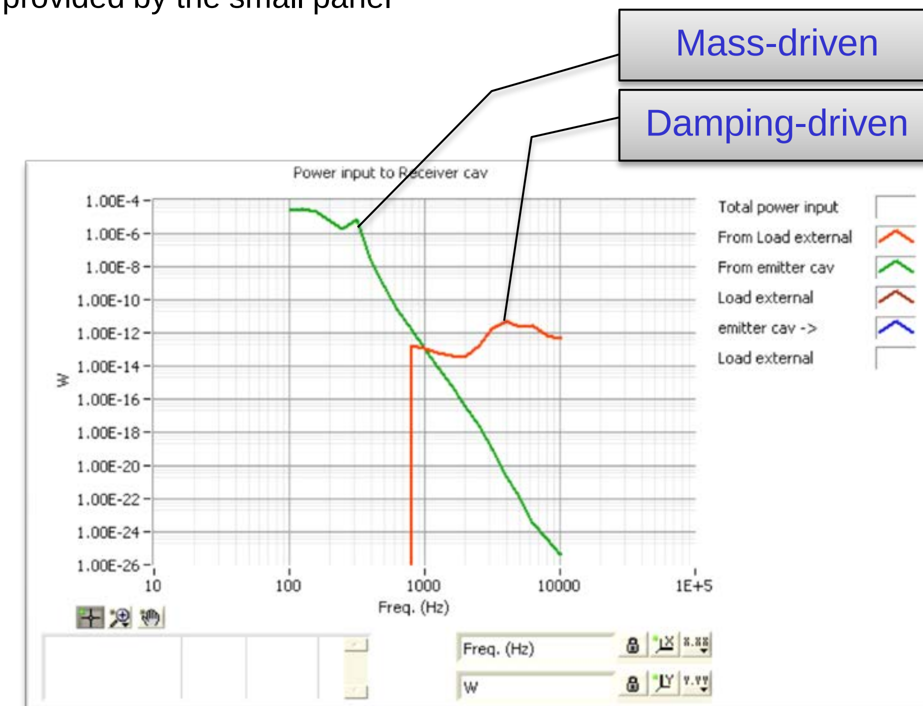
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Predicting noise reduction: transmission path analysis

- In a SEA+ network, both mechanical (SEA structural junctions) and acoustic transmission are modeled
  - These vibroacoustic models are helpful to understand the origin of sound in a receiver volume
  - In next picture, the sound from an emitter cavity is transmitted through a trimmed panel which is mechanically connected to another smaller untrimmed panel which also coupled to the emitter cavity
  - In the right picture, the input power in the receiver cavity is mainly driven above 1000 Hz by the mechanical energy of the trimmed panel provided by the small panel

Power flow at 2000 Hz





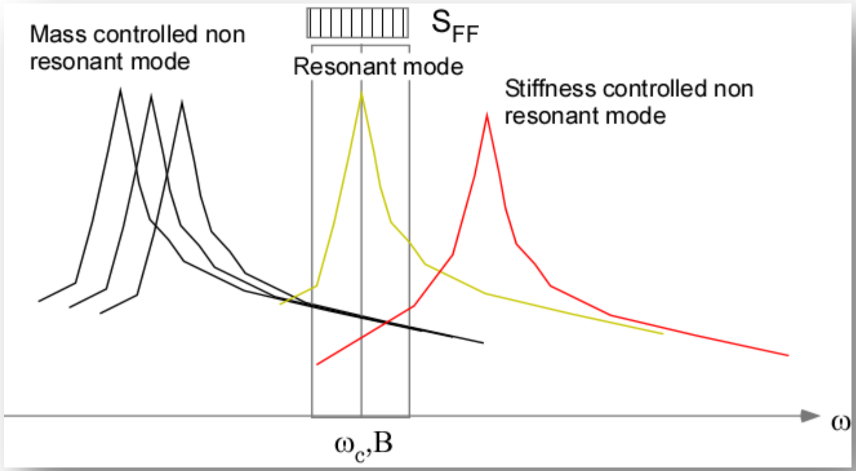
Prediction Using Colored Energies

- Non-resonant transfers of energy in all subsystems are predicted in SEA+. They improve the simulation of energy transfers between subsystems of different wavenumbers.
- To differentiate resonant and non-resonant energies, they are named by color.
- In the analysis band B:

<u>White energy</u> "classical" SEA energy stored in resonances included in B,
white energy is damping dependent

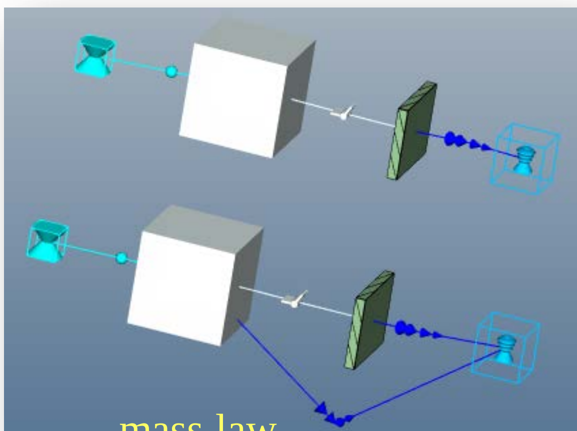
<u>**Black energy**</u> non-resonant energy of modes resonating below B,
black energy is mass dependent

<u>**Red energy**</u> non-resonant energy of modes resonating above B,
red energy is stiffness dependent

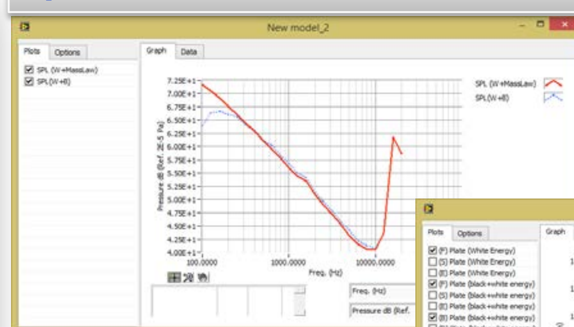


Black Energy/Mass Law

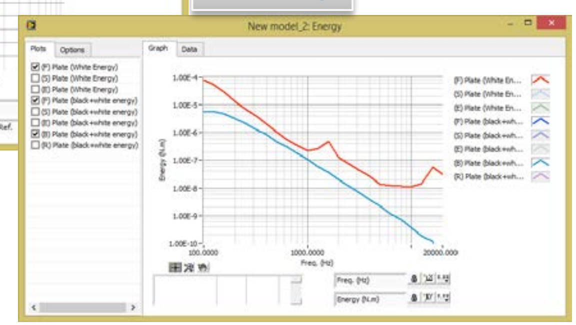
- The mass law connection between the two cavities connected to mid-panel can be removed when the colored energy calculation is enabled in the subsystem
- It gives better accuracy for mass-driven STL especially for curved structures and is faster to compute thanks to the vectorization of Maïdanik algorithm implemented in SEA+ to calculate the non-resonant radiation efficiency of black modes
- It provides also the black energy stored in structures



Spl with mass law and with B-energy



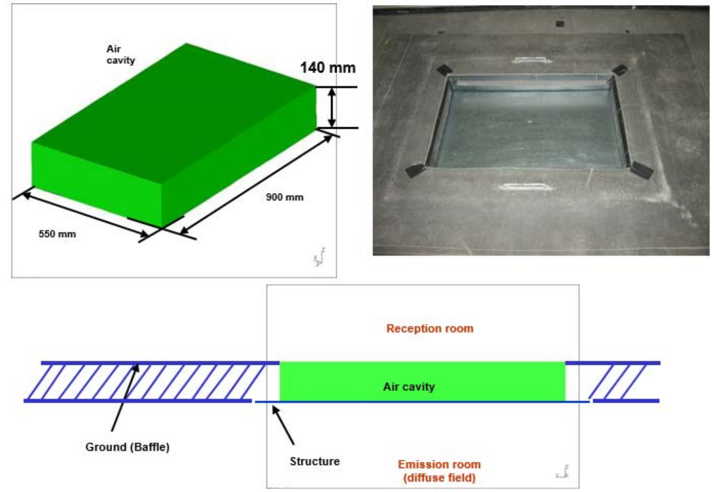
V_W & V_B



Prediction of STL vs Measurements

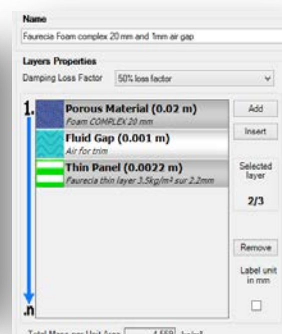
- STL measurements have been provided by Faurecia R&D Research Center in Mouzon
- Several test configurations are predicted for flat geometry and for curved geometry with and without acoustic treatment (trim)
  - Configuration 1: **bare flat panel**
  - Configuration 2: **flat panel + trim**
  - Configuration 3: **bare ½ cylinder panel**
  - Configuration 4: **½ cylinder + trim**

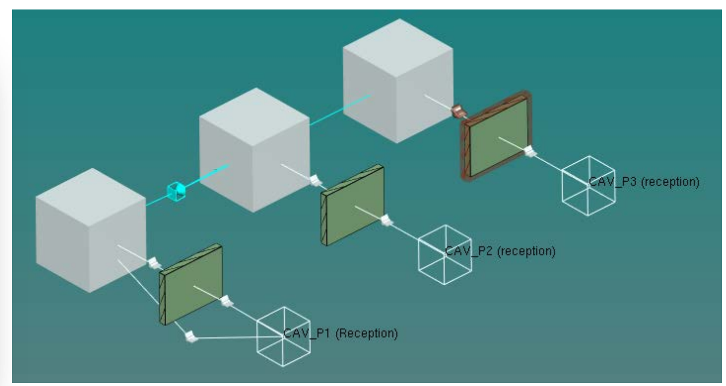
  For each configuration, three calculations:
  - **Model P1**: uses Mass Law with active spatial windowing for non-resonant energy transfer calculation
  - **Model P2:** uses panel black energy for non-resonant energy transfer calculation
  - **Model P3**: adds to Model P2 an air gap (with SEA-Foam library) on panel side for simulating the acoustic niche effect



Bare test panel configuration for TL testing (Faurecia document)

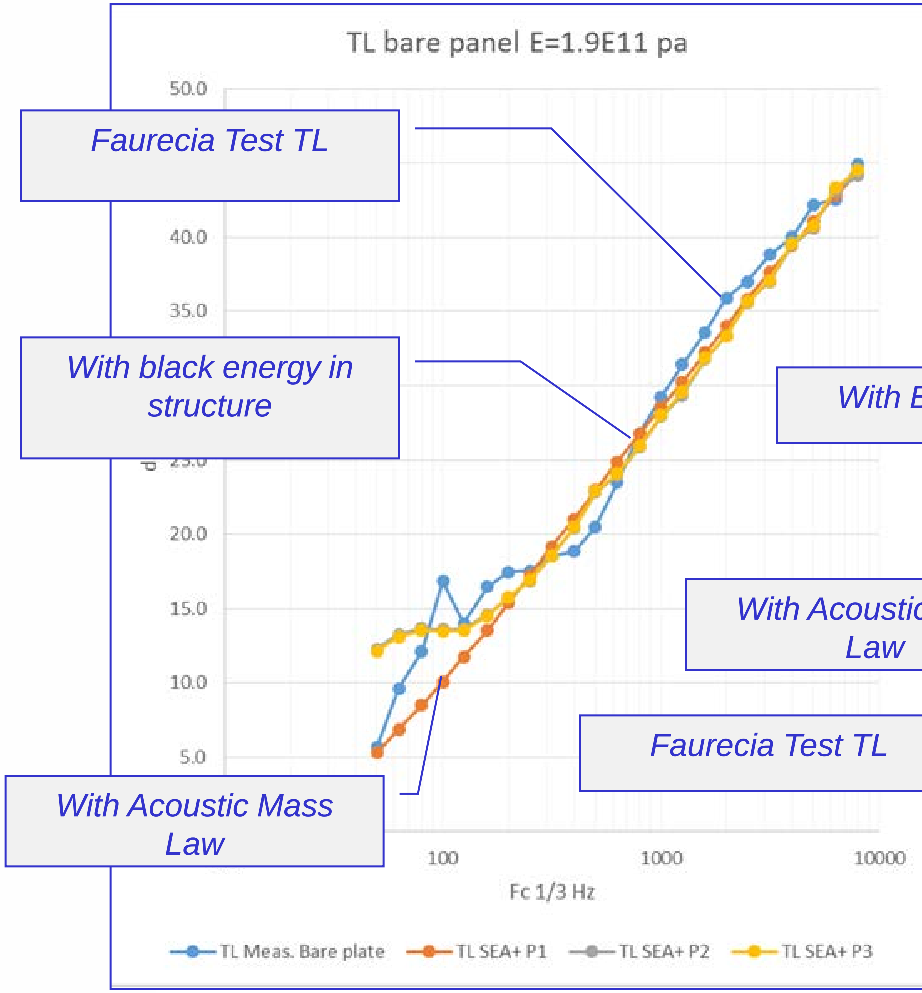
Steel plate – properties	
thickness:	0.8 mm
Modulus of elasticity:	1.9 to 2.1E11 MPa
Poisson's ratio:	0.3
Shear modulus:	8.E10 MPa
Mass Density:	7820 kg/m³

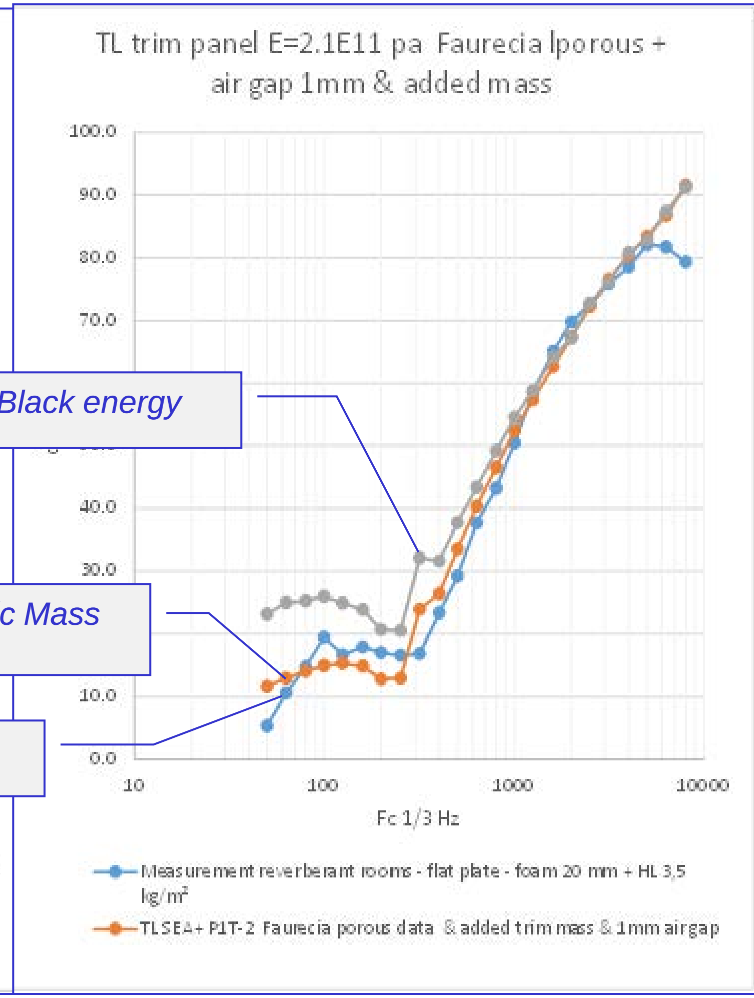




InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

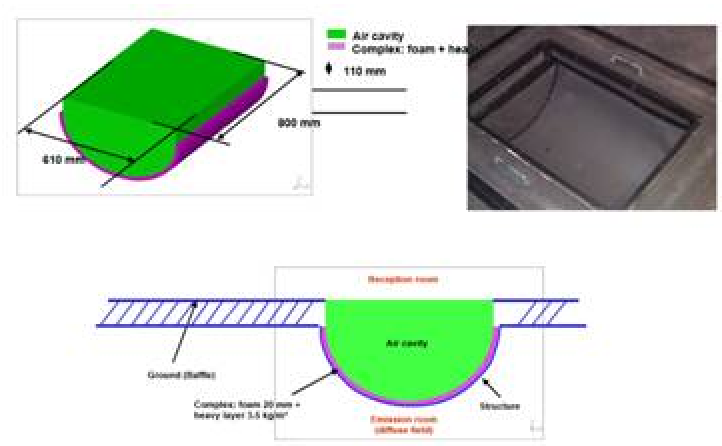
Prediction/Test Configurations 1 (left) and 2 (right)





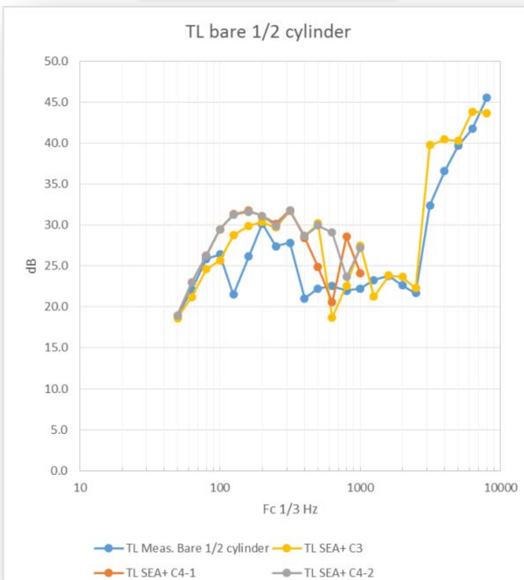
SEA+ STL Prediction vs Measurements Configurations 3 & 4

- For each configuration, three calculations:
  - **Model P1**: uses Mass Law with active spatial windowing for non-resonant energy transfer calculation
  - **Model P2**: uses panel black energy for non-resonant energy transfer calculation
  - **Model P3**: adds to Model P2 an air gap (with SEA-Foam library) on panel side for simulating the acoustic niche effect

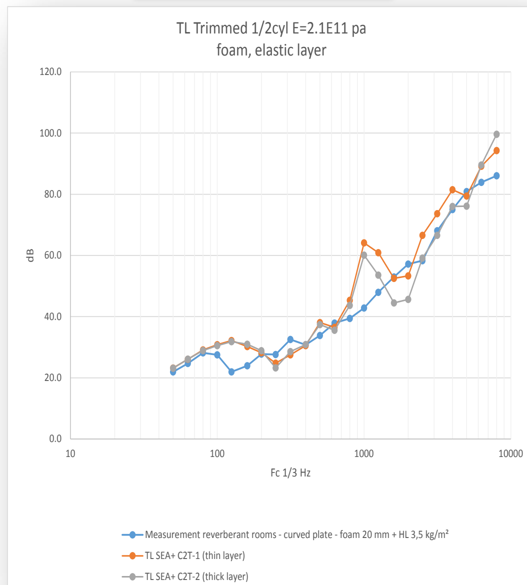


Bare test cylinder configuration for TL testing (Faurecia document)

Configuration 3



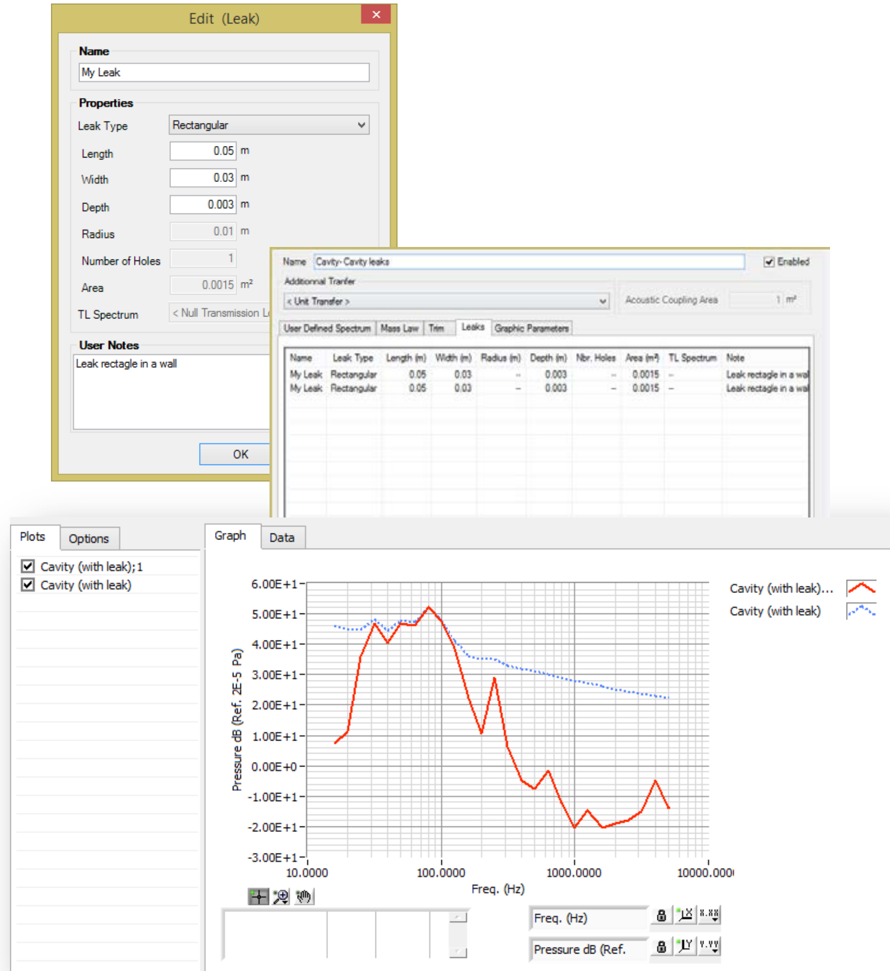
Configuration 4

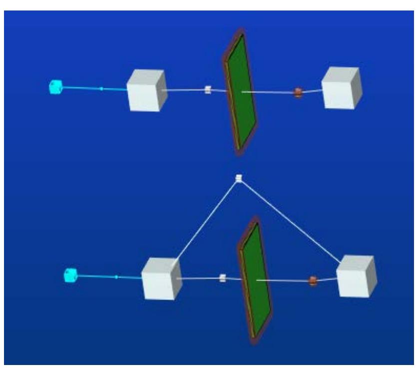


InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Prediction of acoustic leaks

- Leaks are depredating the acoustic performance of a wall
- They are modeled in SEA as small apertures embedded in Cavity-to-Cavity junctions (rectangular, circular or slit)
- They always act in parallel from other sound transmission mechanisms
- They are described by a LEAK SEA object in SEA+ database





VSEA Technique Applied to Car Body

- E_{ij} transfer energy is estimated from a structural FE model using modal synthesis and the loss-matrix is estimated by inverse SEA method
- The automation of the FE-post-processing inverse SEA sequence has been called **Virtual SEA** (**VSEA**) which transforms FE FRF into SEA network using following steps

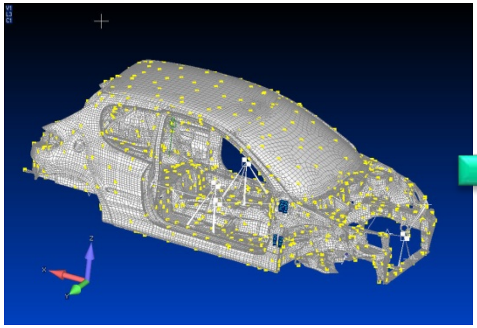
Band integrated FRF matrix generation when exciting FEM model with random point-forces on a grid of reference nodes

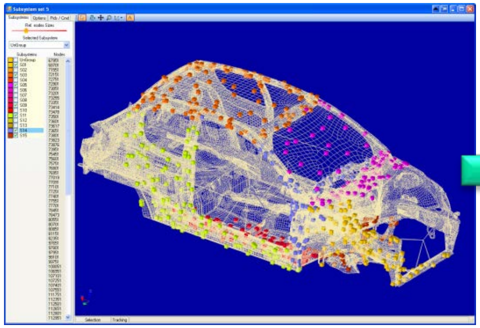
Auto-substructuration

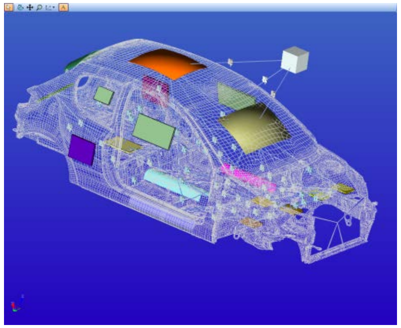
Grouping nodes to create subsystems

Compression into Mean FRF/subsystem matrix

Inverse technique to identify SEA parameters

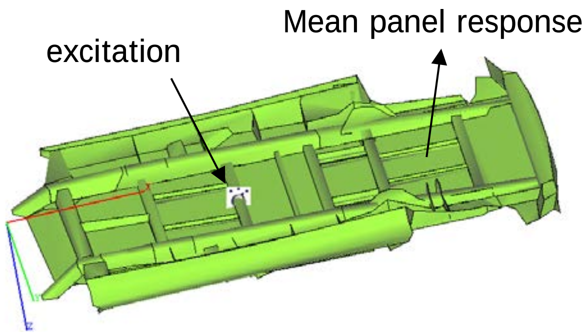


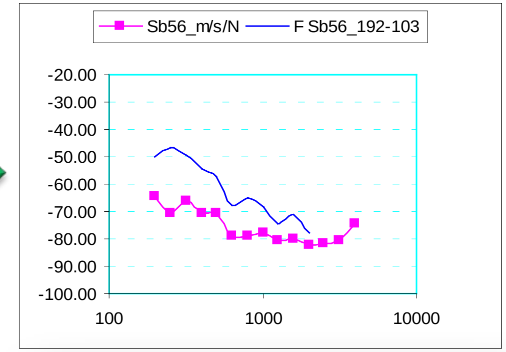




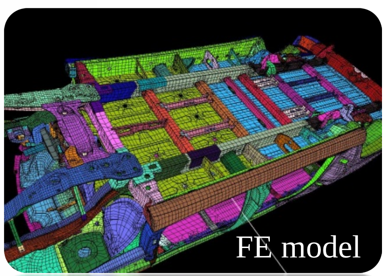
Validation example: car chassis structure borne sound

Analytical SEA model

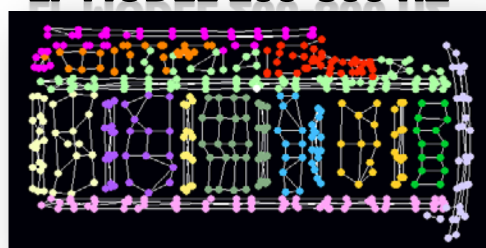


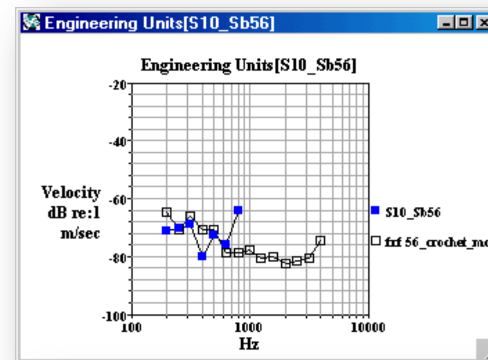


Virtual SEA model

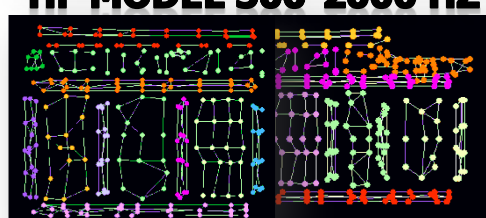


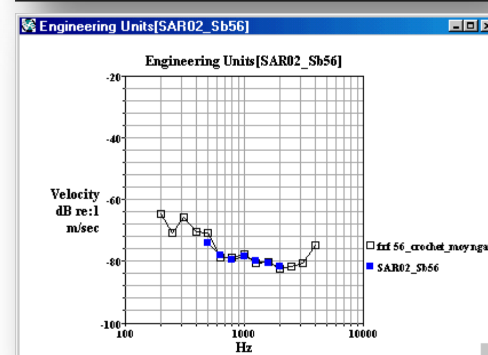
LF MODEL 200-800 HZ





HF MODEL 500-2000 HZ

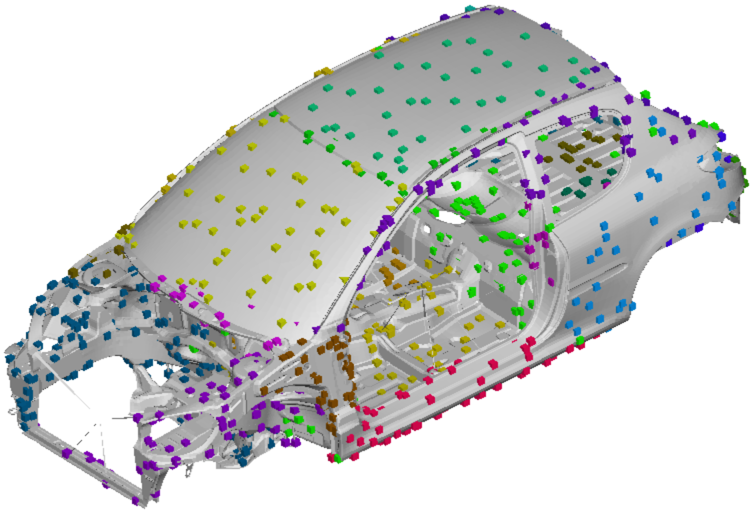


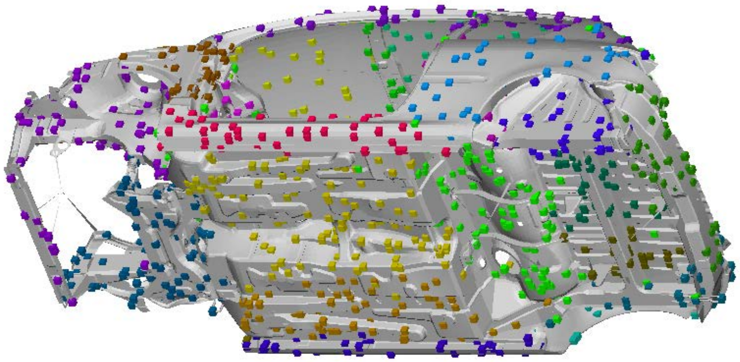


InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

1- Virtual SEA Model Creation

- Solving Nastran model up to 1 kHz
- Subsystems determination
- SEA parameter identification

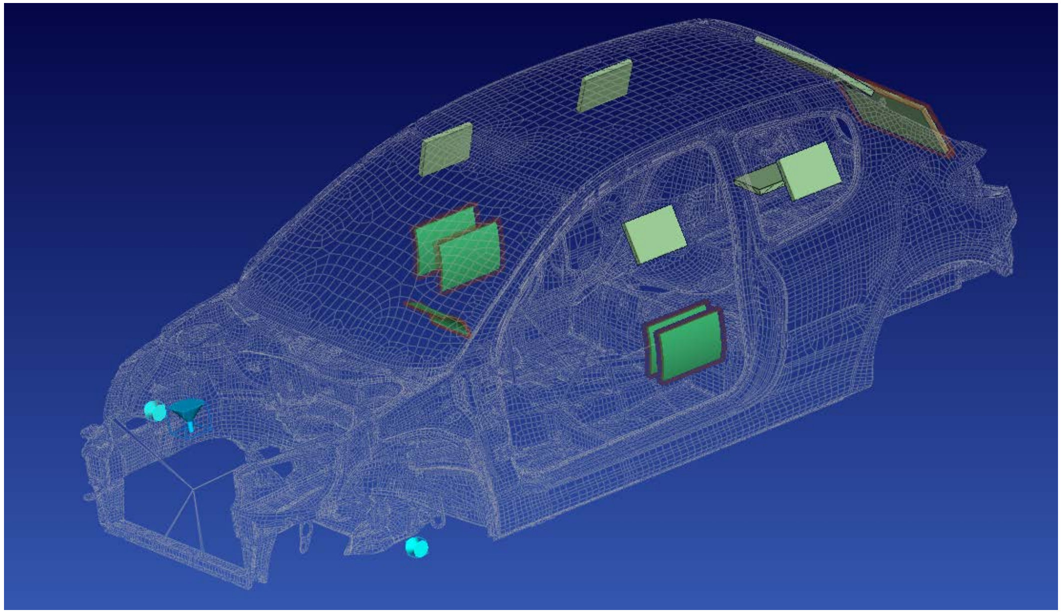




2- Adding Missing Structural Subsystems

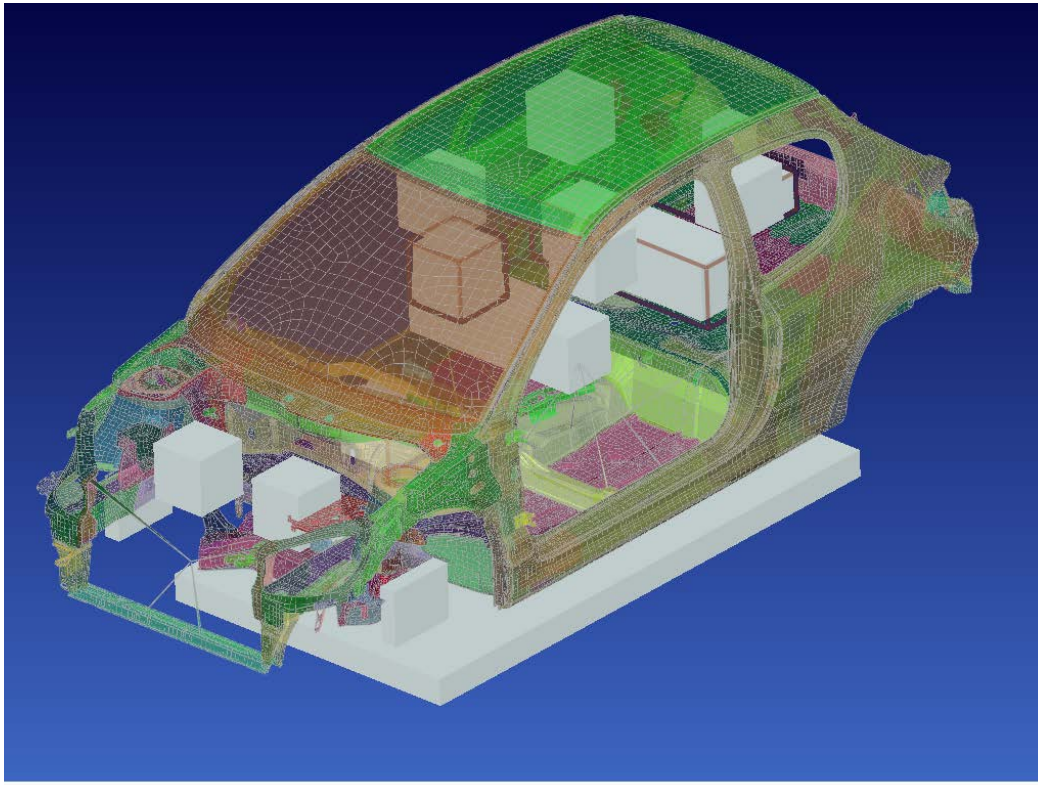
- Analytical structural subsystems are added as they were not present in the FEM

- They are coupled to virtual SEA subsystems



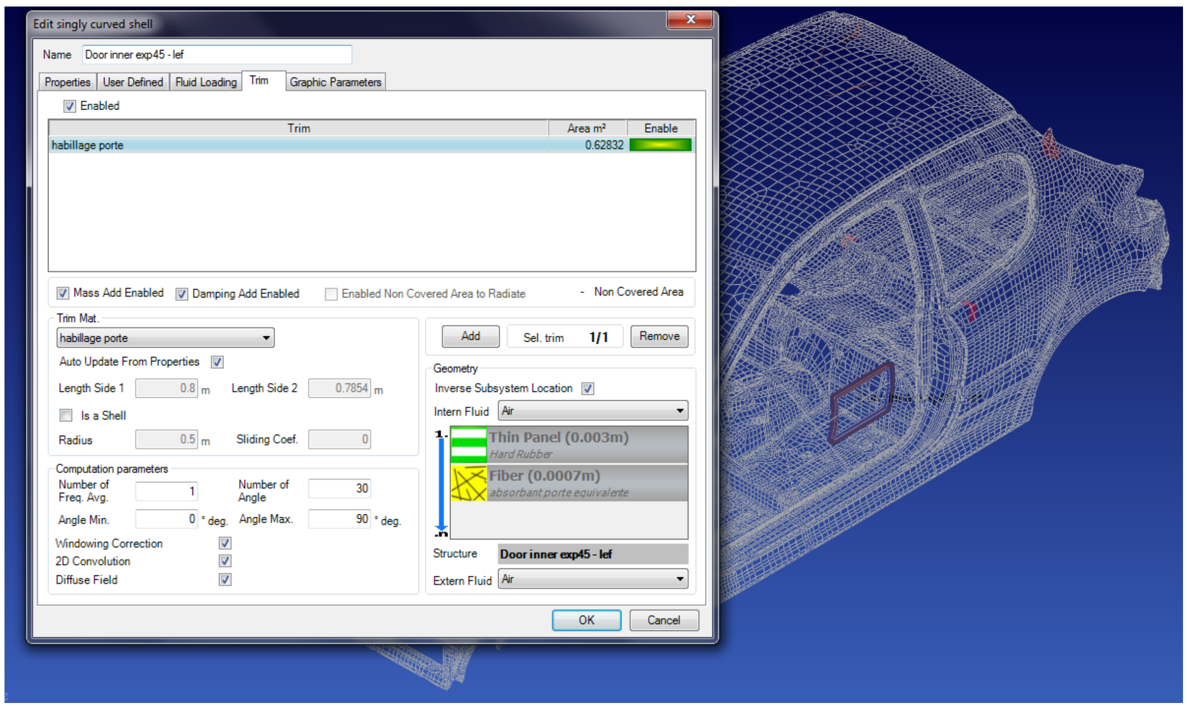
3- Adding Acoustic Cavities

- Analytical acoustic subsystems are added
- They are coupled to virtual and analytical structural SEA subsystems



4- Adding Trims to Subsystems

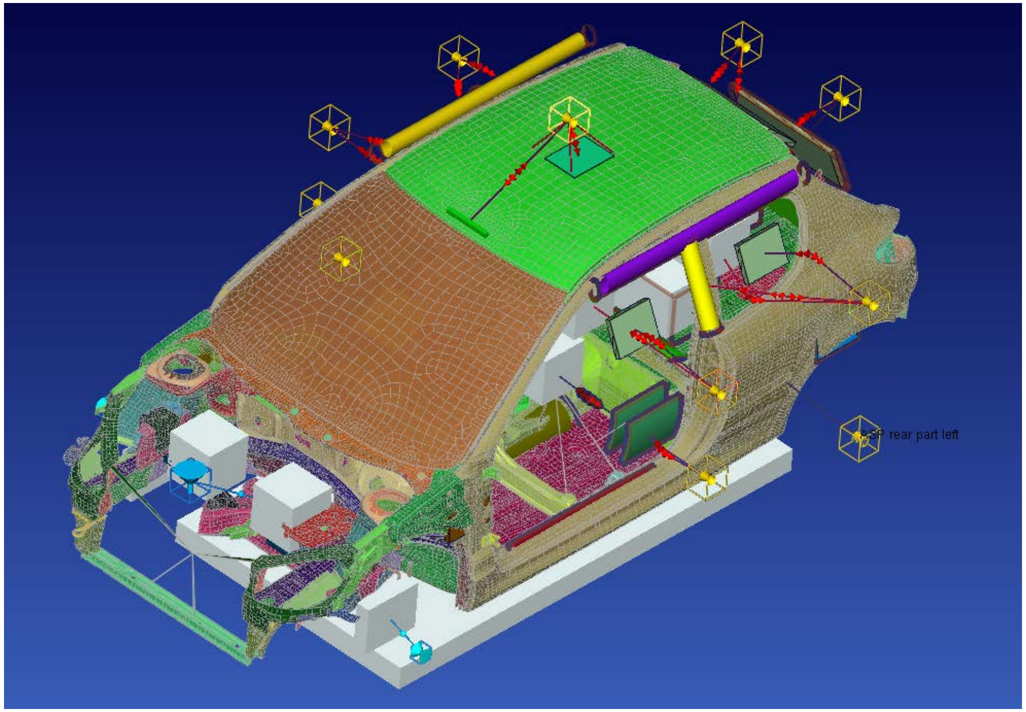
- Trims are defined through TMM formulation
- Specific correction for curved insertion
- Spatial windowing for all TL-IL prediction
- Added mass and damping predicted



InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

5- Adding Load Cases

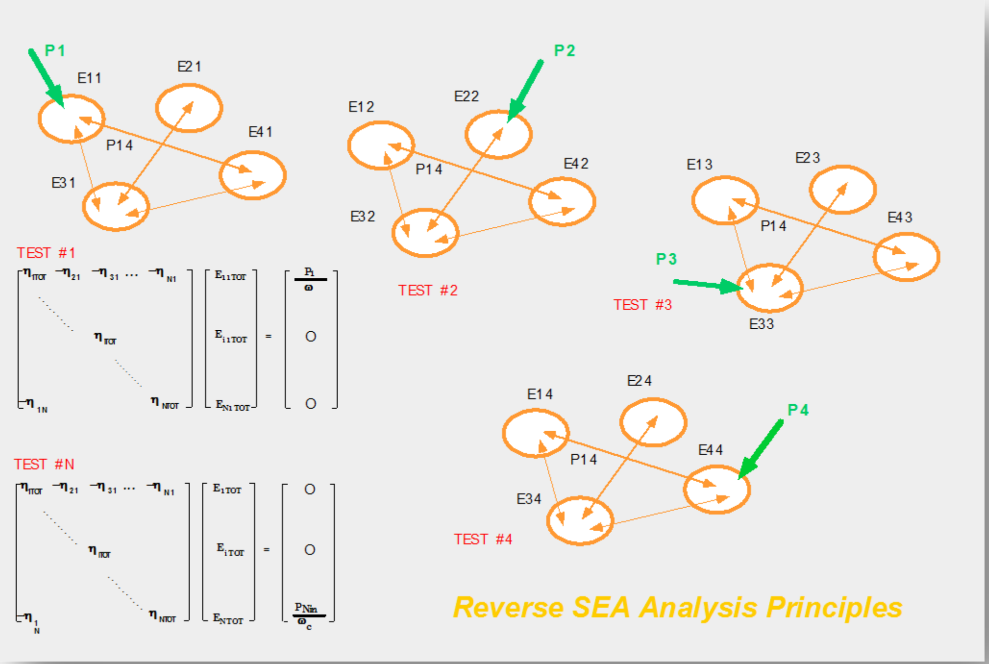
- Local pressure application (**ASP**) to subsystems
- Embedding free field transfer between sources and ASP



Full car SEA model analysis (including all paths)

- The analysis combines ESEA measurement and modeling combined with ASEA model
- All structures including internal trims are included in the ASEA model

Experimental SEA analysis

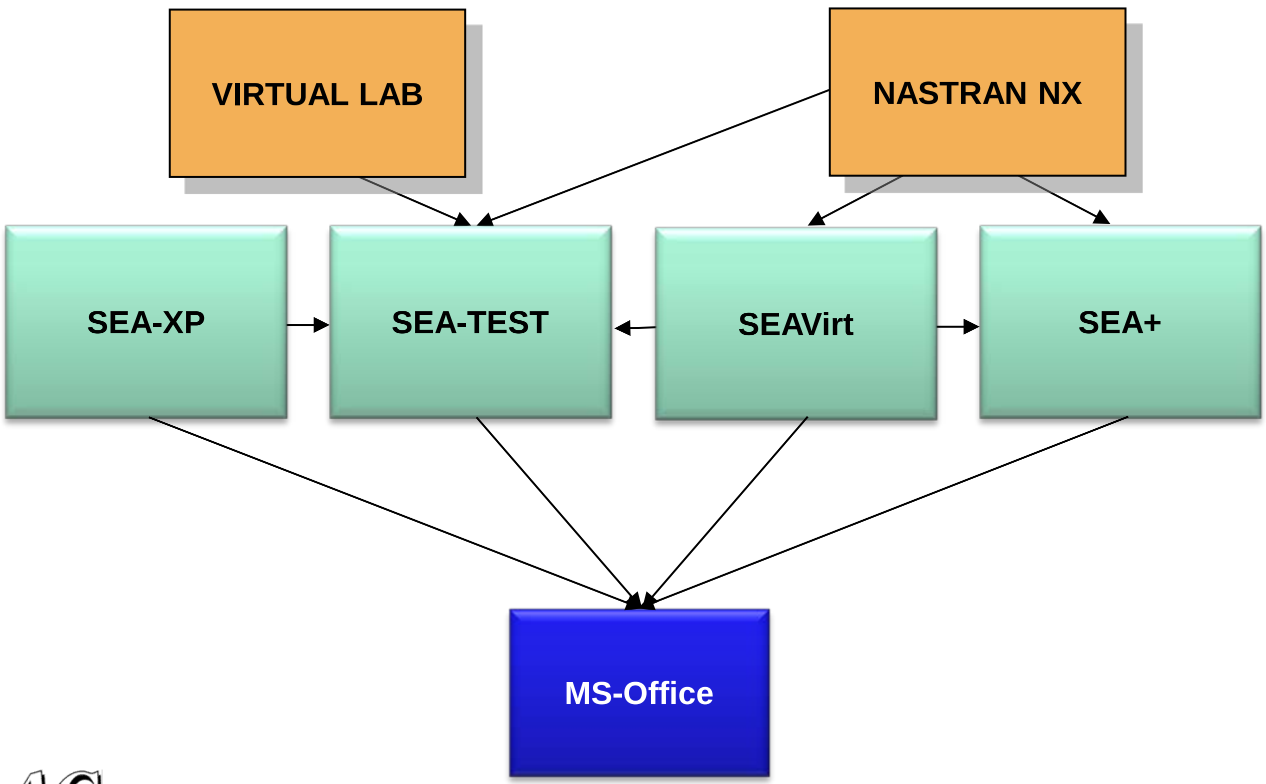


- Subsystems are excited at a turn using calibrated input power (impact hammer, shaker or loud-speaker)
- For each excitation case, FRF are measured between a grid of points that map the system
- One can thus write at the end a linear system of equations relating FRF, DLF, CLF and Input power
- Inverting some subset of the FRF matrix, leads to either DLF or CLF solution

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

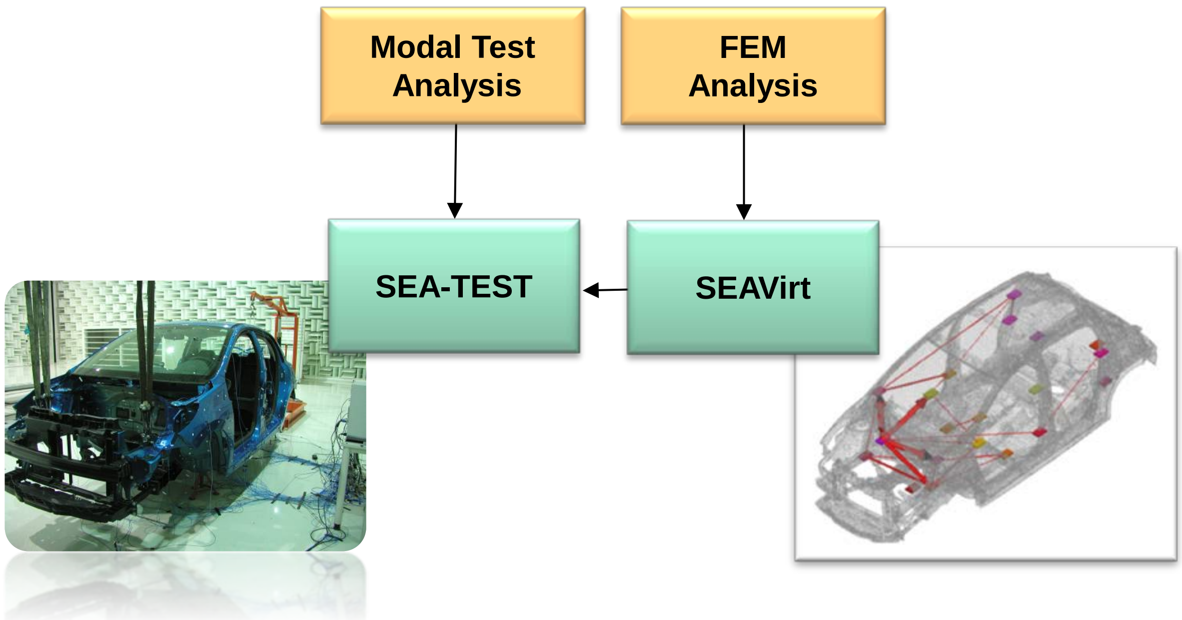
Strategy of data hybridization/validation

- SEA model robustness is improved by hybridization of test and calculated data. Theoretical modelers and data acquisition systems can dynamically, or via import/export functions, exchange data for more efficient model creation



Collaborative Work with SEA-TEST

- Starting from a NASTRAN FEM model, SEAVirt generates the related virtual experimental SEA model, providing automatically the well-adapted decomposition into subsystems
- SEA-TEST may share the same TEST protocol: SEA-TEST and SEAVirt models can be directly compared
- Subsystems sets obtained by SEAVirt can be directly read by SEA-TEST



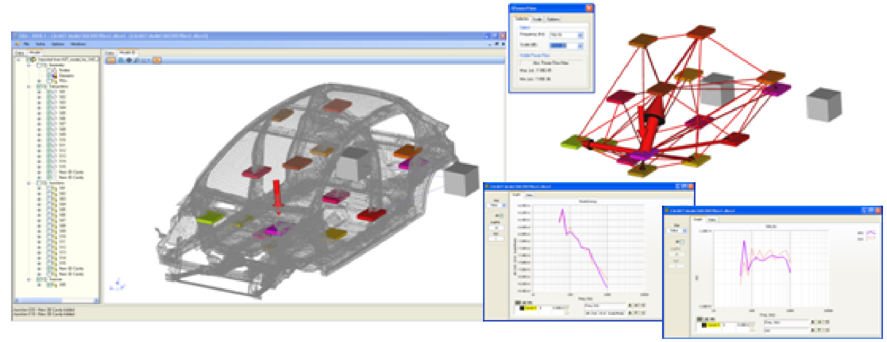
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

VSEA for structure-borne prediction

Using VSEA models

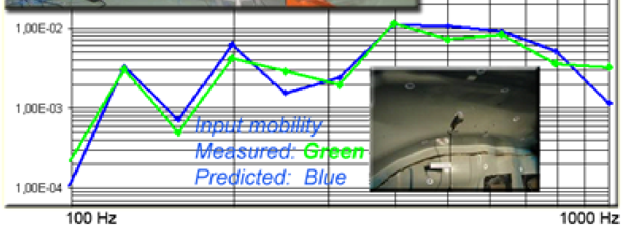
With the VSEA software manager, created models may be coupled to standard analytical SEA subsystems such as acoustic cavities or plates to compute sound transmission problems (for cars) or acoustic random vibrations (for spacecrafts)

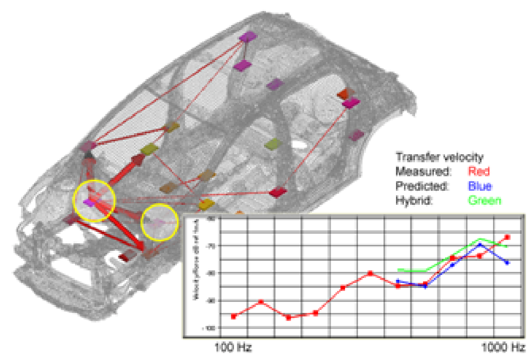
Excitations may be applied to all individual nodes of the VSEA model or on average on the subsystem



VSEA Full car validation (Faurecia-PSA)

- Measurement of all SEA subsystems obtained from VSEA using SEA-TEST experimental SEA software
- Comparison of predicted and measured structural transfers
- Analysis of damping provided by trims





- 64 fixed accelerometers on the structure shared out among the different subsystems where input power measurements have been performed
- 1048 points on the structure hit one by one with hammer in order to measure transfer functions between these points and the fixed accelerometers (reciprocal protocol)

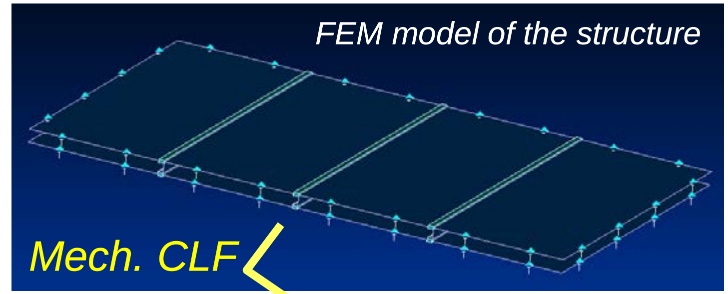
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

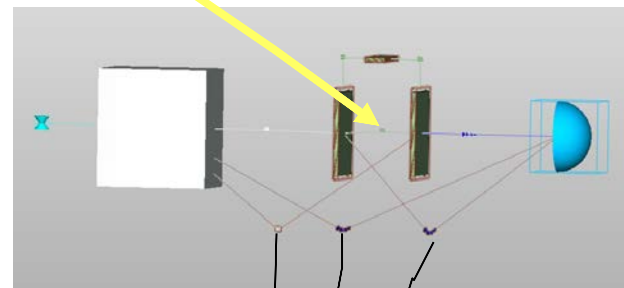
Adding mechanical transmission between elastic layers

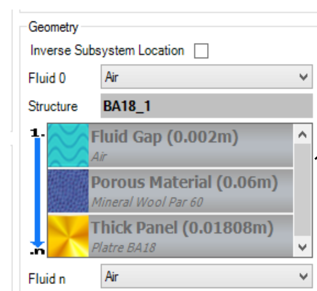
- SEA+ offers analytical line and point junction models with interface boundary conditions in which periodic ribs can be inserted to get the mechanical CLF between elastic layers
- The inserted rib is described by a 4 x 4 static elastic impedance matrix

$$\begin{bmatrix} N \\ S \\ T \\ M \end{bmatrix} = Z_M \begin{bmatrix} U \\ V \\ W \\ \Theta \end{bmatrix}$$

- Mechanical CLF can be alternately predicted from FEM related structural model





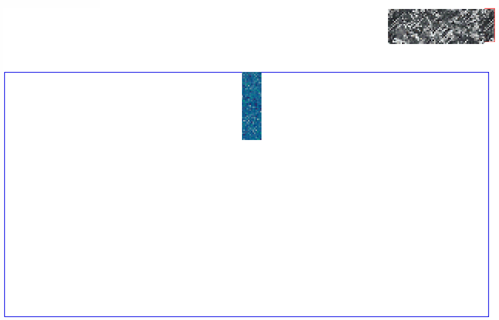


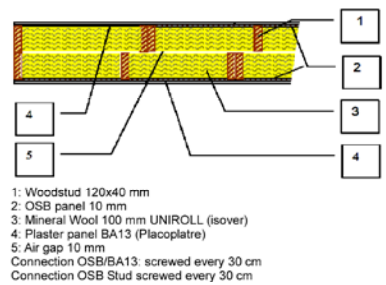
TMM for describing acoustic insertion loss due to 2nd leaf screening the 1st

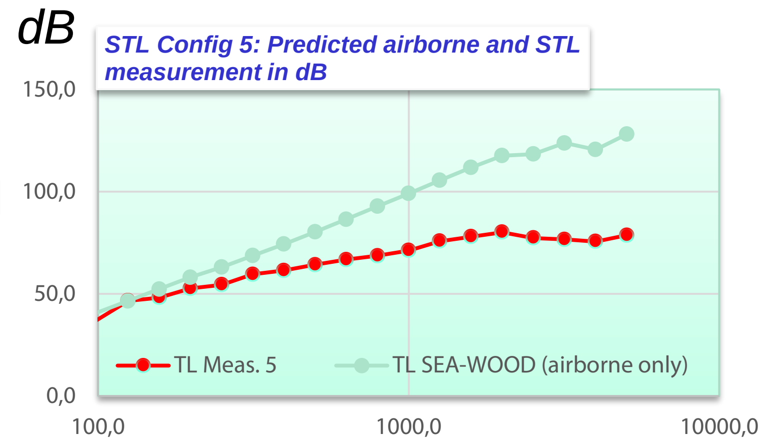
InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Prediction of TL of composite wall (for timber-framed buildings)

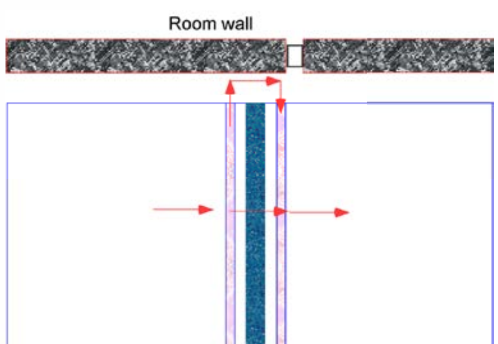
Air borne path only/measurement

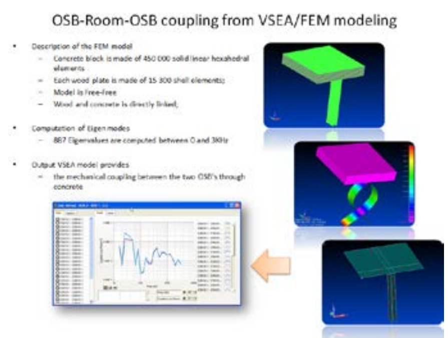


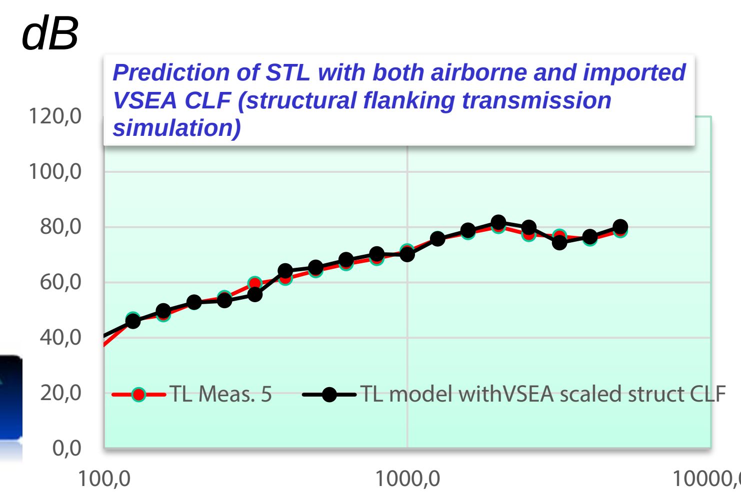




Airborne path + structure borne/measurement







InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Damping Prediction with Dynamic Laminate

- Dynamic Laminate construction is designed to predict modal density, wavenumber, mobility and damping of a superposition of 2D glued thin layers

- The Dynamic Laminate is based on an original theory assuming the shear and compression strain along vertical z-axis behave as static

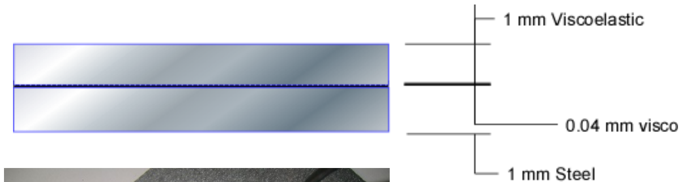
- The elementary layers are defined by their orthotropic elastic characteristics and damping which can also vary with frequency

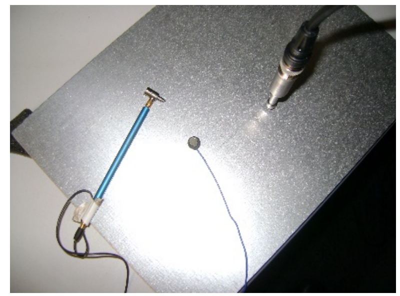
- Plates with viscoelastic insertion or sandwich panels with honeycomb core are handled by this theory

- Cylinders and doubly-curved shells are also supported

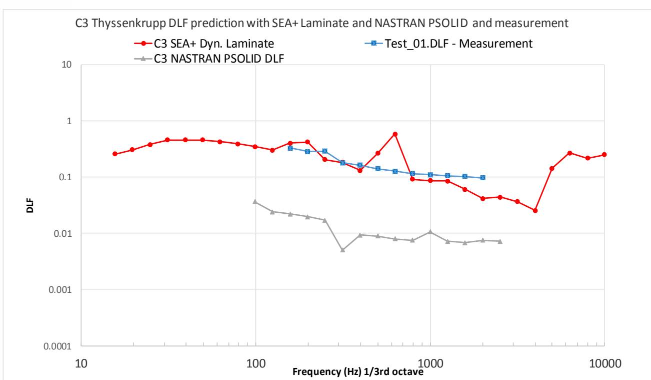
Modeling Damped Steel Plate

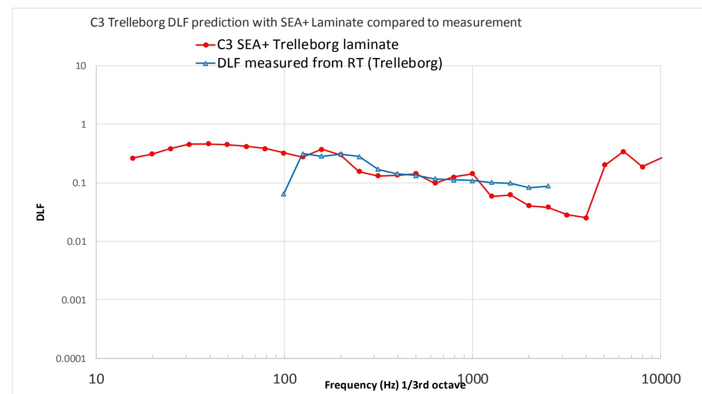
- A 3-layered steel panel with very thin film of viscoelastic
- 0.275 m x 0.2 m
- Comparison of predicted DLF with Test measurement (impact hammer) and FEM PCOMP and PSOLID models





Layer	Density (kg/m3)	E (Pa)	G (Pa)	ν	DLF
Skin	7800	2E11	8E10	0.3	0.01
Visco	1600	5E7	2E7	0.2	1
Skin	7800	2E11	2E11	0.3	0.01





Left ThyssenKrupp panel; simulated (Dynamic Laminate, PSOLID) and measured DLF; Right Trelleborg panel, simulated (Dynamic Laminate) and measured DLF

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics

Conclusions

SEA is a high frequency method which predicts random responses in complex systems as soon as the model is well designed (weak coupling between subsystems, predominant modal response).

SEA theory is the right asymptotic behavior of dynamical systems in the HF range.

From input power injected by external loads, SEA provides the levels of energy stored in subsystems as well as power flow between them, useful to rank transmission paths.

Virtual SEA improves ability to create complex and robust SEA structural models with FEM-liked accuracy addressing structure borne path identification. It provides to engineers power of FEM in SEA analysis.

Combining Virtual SEA and analytical SEA extends energy models to mid-frequency, a major breakthrough in SEA projects.

Thank you

InterAC
Ingénierie Technique & Recherche en Acoustique
Technical Engineering & Research in Acoustics