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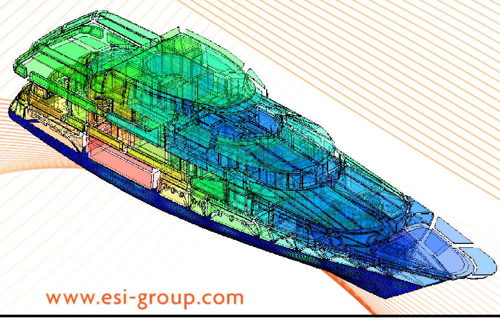
19th International
Conference on Traffic Noise

"FE/SEA Coupled"
A breakthrough in Aerospace, Rail, Automotive and Ship Noise Prediction (Vessel noise aspects)



Denis Blanchet, Arnaud Caillet,
ESI GmbH, Sept 10, 2010

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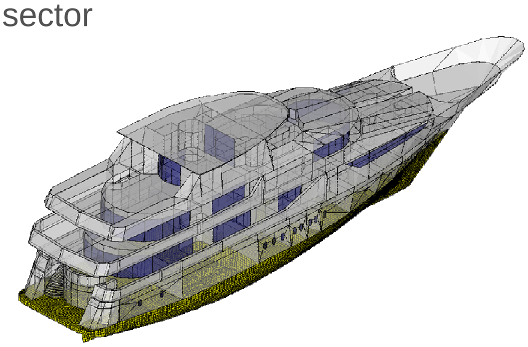
Outline

- Context
- Introduction to FE/SEA Coupled
- Examples in aerospace, automotive, rail application
- Examples in marine sector
- Conclusion



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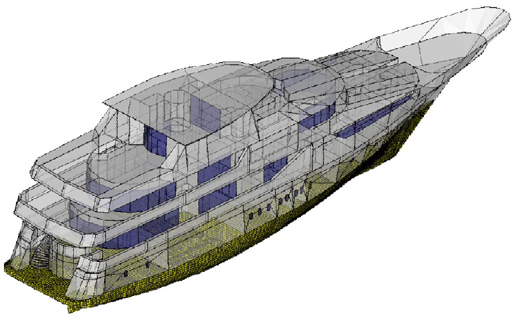

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Context

- Rapid prototyping requires increased use of simulation
- Full frequency analysis needed to fully diagnose vibro-acoustic performance
- Minimum computation time to allow optimization
- Predictive simulation removes need for physical prototype until late in a design process
- …

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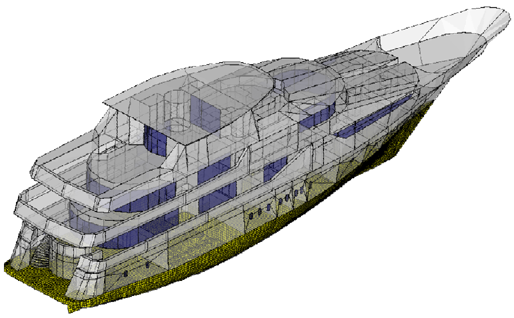

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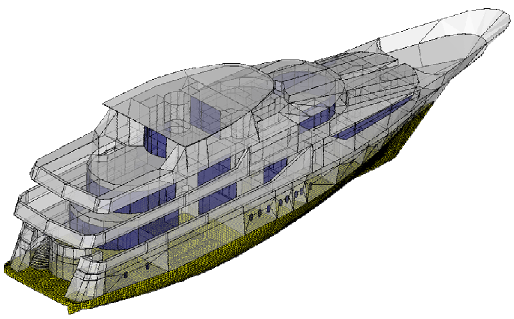

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The "FE/SEA Coupled" approach

Rigorously couples deterministic and statistical methods within a single vibro-acoustic model (VA One)

Replace with images from the yacht model

Deterministic

Statistical

"FE/SEA coupling"

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Numerical methods involved

- Low Frequency Analysis:
  - Finite Element Method (FEM) is well suited for structure and acoustic fluid where a low number of modes are present
  - Provides good representation of physics in frequency range where boundary conditions (BC) influence results
  - Boundary Element Method (BEM) is well suited for low frequency representation of fluid but computationaly expensive
  - Fast Multipole Method (FFM) is used to increase efficiency of BEM computation (Here, all BEM results are computed using FMM)
- High Frequency Analysis:
  - Statistical Energy Analysis (SEA) has been widely used for vibro-acoustic predictions at high frequency
  - Well suited to describe large structure or acoustic fluid where many modes are present
  - Extensively used in aerospace, aircraft, automotive, train industry. Gaining acceptance and being adopted the marine community

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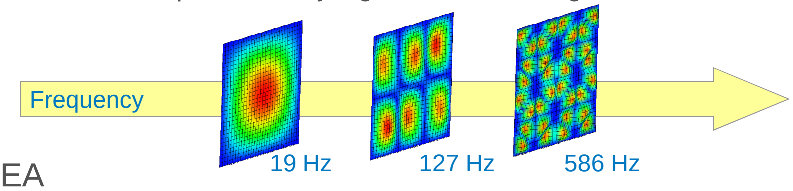
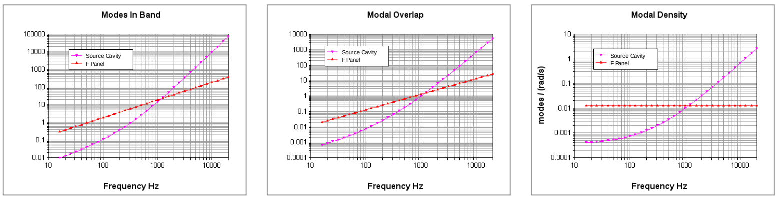
Modes representation

- FEM:
  - Modes are represented by eigen values and eigen vectors



- SEA
  - Modes are represented by modal density



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Numerical methods investigated

- Full Frequency Analysis:
  - Combination of detailed FEM representation of the very stiff structural elements and SEA representation of the more flexible structural elements. Cavities can generally be modeled in SEA as well.
  - FEM and SEA elements are coupled together through the use of “FE/SEA Coupled” formulation (hybrid coupling)
  - Any part of the system can be excited with typical loads applicable to FEM and SEA

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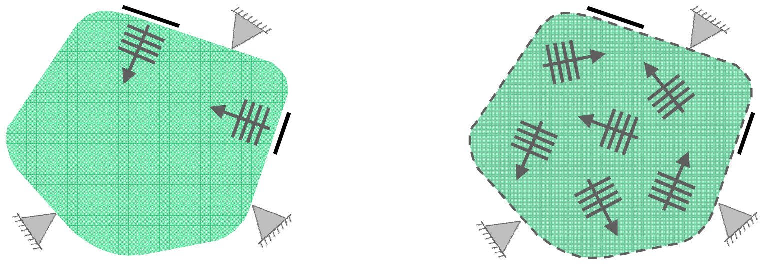
Introduction to FE/SEA Coupled

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

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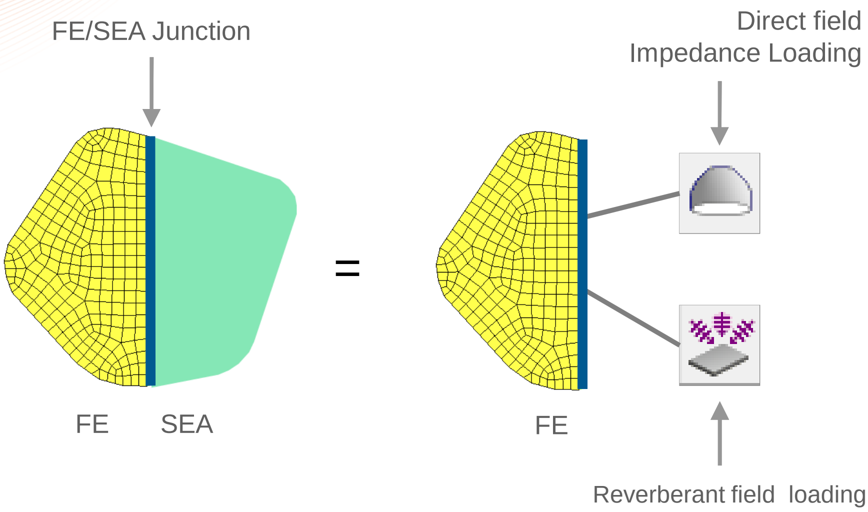
Introduction to FE/SEA Coupled



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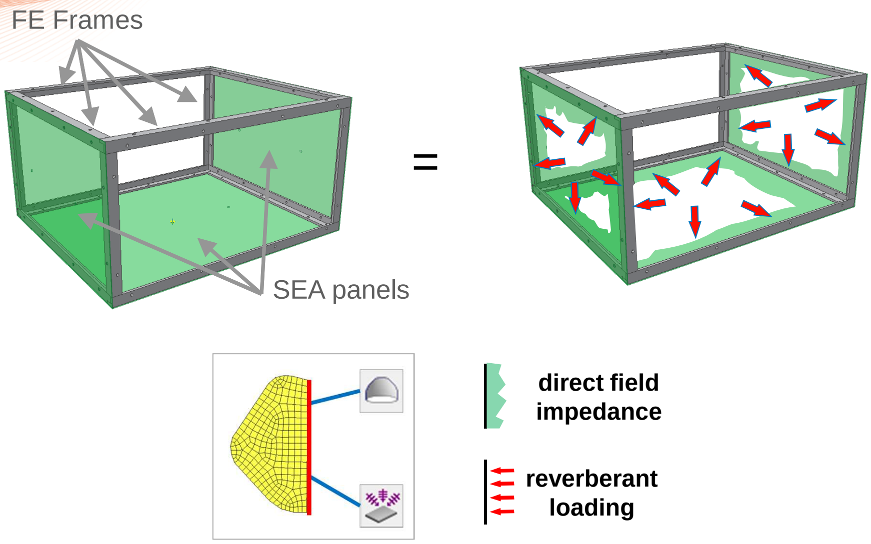
Introduction to FE/SEA Coupled



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Introduction to FE/SEA Coupled

Paper 1

On the reciprocity relationship between direct field radiation and diffuse reverberant loading

P. J. Shorter[a] and R. S. Langley[b]
ESI US R&D Inc., 12555 High Bluff Drive, Suite 250, San Diego, California 92130

(Received 23 January 2004; revised 19 July 2004; accepted 7 September 2004)

This analysis is concerned with the derivation of a "diffuse field" reciprocity relationship between the diffuse field excitation of a connection to a structural or acoustic subsystem and the radiation impedance of the connection. Such a relationship has been derived previously for connections

First paper provides a proof that "the ensemble average reverberant loading for a connection to a subsystem with uncertain boundaries is proportional to the direct field radiation impedance of the connection.
A generalised "diffuse field" reciprocity result

reverberant loading $\propto$ direct field impedance

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Introduction to FE/SEA Coupled

Paper 2

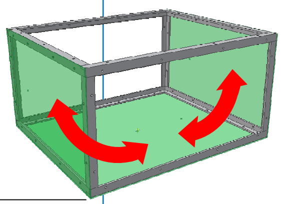
Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Sound and Vibration 288 (2005) 669–699
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Vibro-acoustic analysis of complex systems

P.J. Shorter*, R.S. Langley[1]
ESI US R&D Inc., 12555 High Bluff Drive, Suite 250, San Diego, CA 92130, USA

Accepted 5 July 2005
Available online 2 September 2005

Abstract



Second paper shows how reciprocity result can be used to derive a general analysis method for predicting ensemble average response of coupled deterministic and SEA subsystems. Approach can be viewed as a generalization of the wave approach to SEA. Expressions are derived for the additional ensemble average CLFs between all SEA subsystems that arise due to the presence of the FE subsystems.

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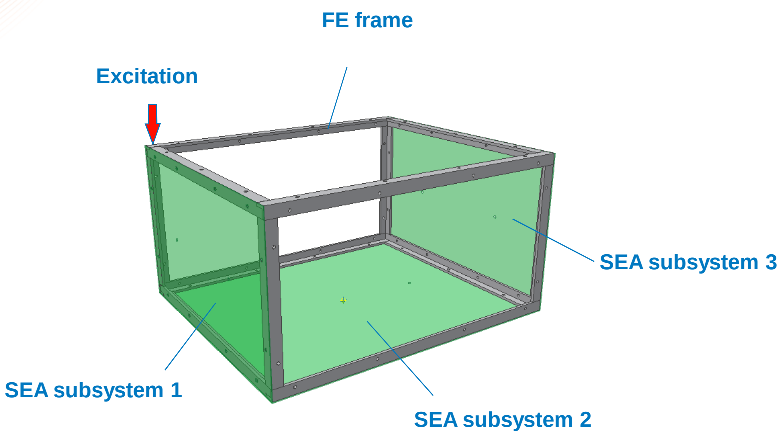
Theory example



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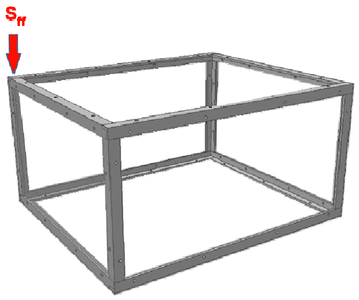
Step 1:
Write EOM for FE subsystems



$$[\mathbf{D}_0]\{\mathbf{x}\} = \{\mathbf{f}\}$$

Dynamic stiffness of deterministic subsystems

= [K-w2 M]

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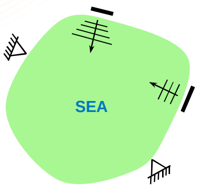
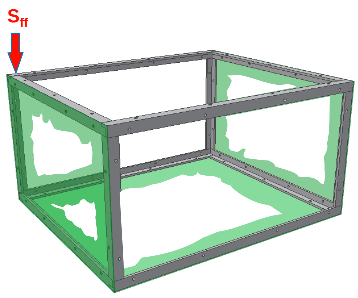
Step 2:
Add SEA direct field impedances



Direct field

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



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

Dynamic stiffness of SEA subsystem direct fields calculated at each hybrid point and line junction.

Direct field impedance has resistive and reactive components.

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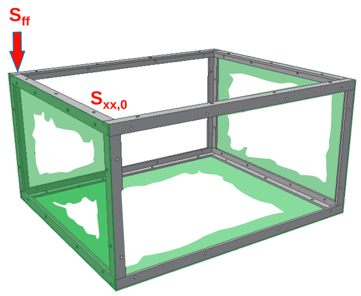
Step 3: Compute cross-spectrum response on FE



Cross spectrum of response on FE beam due to excitation [S_{ff}] and loading from SEA subsystems

$$\mathbf{S}_{xx,0} = \mathbf{x}\mathbf{x}^H = \mathbf{R}\mathbf{S}_{ff}\mathbf{R}^H$$

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

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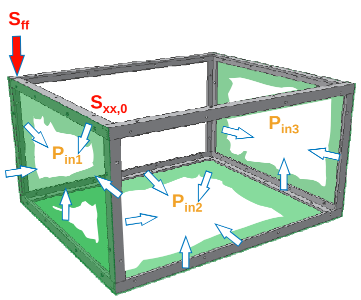
Step 4: Compute direct field input power



Input power to direct field of i'th SEA subsystem related to cross-spectrum of response S_{xx}

$$P_{in,i} = \frac{\omega}{2}\,\mathrm{Im}\left\{\sum_{mn}\left(\mathbf{S}_{xx,0}\right)_{mn}\left(\mathbf{D}_{i,dir}\right)_{mn}\right\}$$

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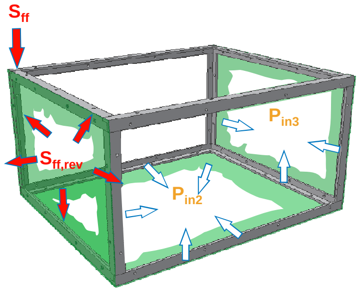
Step 5: Compute Hybrid CLFs between SEA subsystems



Apply reverberant loading in *i*'th SEA subsystem, find input power into direct fields of subsystems *j* ...

$$\mathbf{S}_{ff,rev,i} = \frac{4E_i}{\pi\omega n_i}\,\mathrm{Im}\left\{\mathbf{D}_{dir,i}\right\}$$

Diffuse field reciprocity relation

$$\eta_{ij} = \frac{P_{in,j}}{\omega E_i}$$

Hybrid CLF

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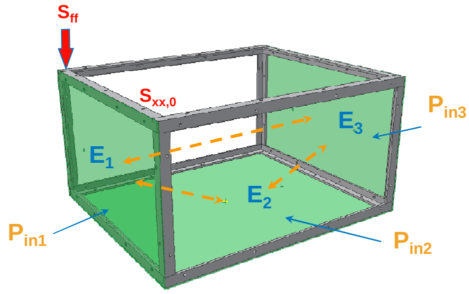
Step 6: Solve SEA power balance equations



Solve for SEA subsystem energies

$$\omega \begin{bmatrix} \eta_1 n_1 + \sum_{j\neq 1} n_i\eta_{ij} & -n_2\eta_{21} & \cdots & -n_N\eta_{N1} \\ -n_1\eta_{12} & \eta_2 n_2 + \sum_{j\neq 2} n_i\eta_{ij} & & -n_N\eta_{N2} \\ \vdots & & \ddots & \\ -n_1\eta_{1N} & -n_2\eta_{2N} & & \eta_N n_N + \sum_{j\neq N} n_i\eta_{ij} \end{bmatrix} \begin{bmatrix} \frac{E_1}{n_1} \\ \frac{E_2}{n_2} \\ \vdots \\ \frac{E_3}{n_3} \end{bmatrix} = \begin{bmatrix} P^{(0)}_{in,1} \\ P^{(0)}_{in,2} \\ \vdots \\ P^{(0)}_{in,N} \end{bmatrix}$$

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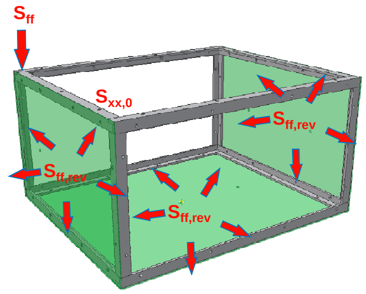
Step 7: Recover response of FE and SEA subsystems

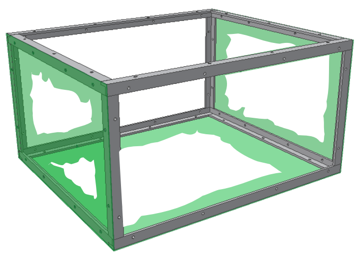


Total response is sum of response to external excitation and reverberant loading of each subsystem

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

SEA direct field impedances

Need "direct field impedance" matrix for each SEA subsystem!



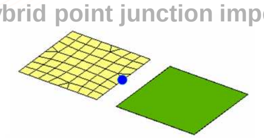
$$\left[\mathbf{D}_0 + \sum_i \mathbf{D}_{i,dir}\right]\{\mathbf{x}\} = \{\mathbf{f}\}$$

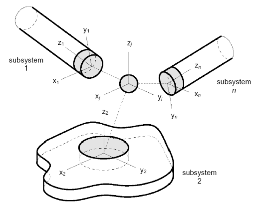
Dynamic stiffness of SEA subsystem direct fields

SEA direct field impedances

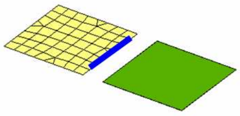
Impedances summed over all hybrid junctions attached to SEA subsystem

Hybrid point junction impedance

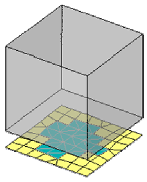




Hybrid line junction impedance



Hybrid area junction impedance



[5] R. Langley and P. Shorter, "Diffuse wavefields in cylindrical coordinates," J. Acoust. Soc. Am. **112**, 1465–1470 (2002).
[5] R. Langley and P. Shorter, "The wave transmission coefficients and coupling loss factors of point connected structures," J. Acoust. Soc. Am. **113**, 1947–1964 (2003).

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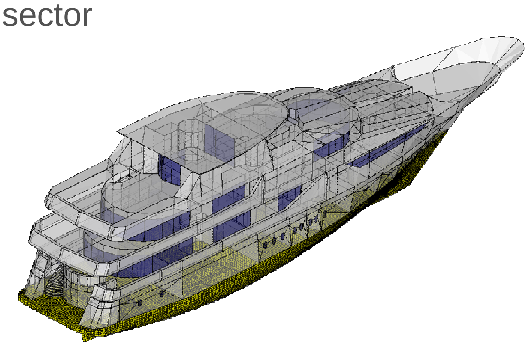
- Introduction to FE/SEA Coupled
- Examples in aerospace, automotive, rail application
- Examples in marine sector
- Conclusion



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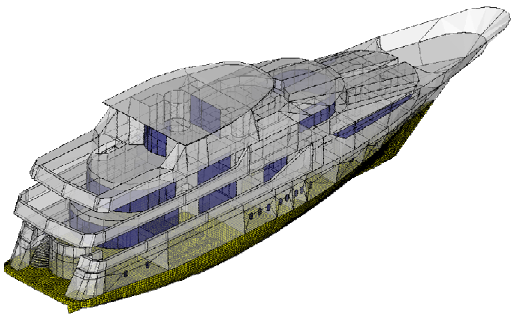

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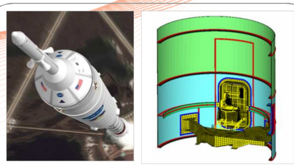
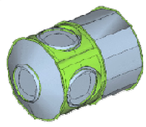
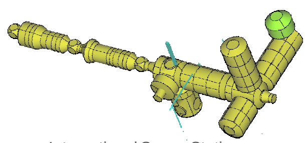
Examples in aerospace



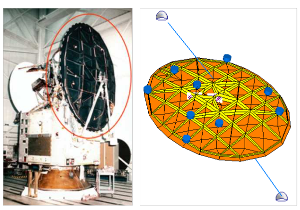
Ares IX, RCS - ATA



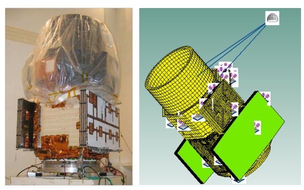
ISS Node3 - Thales Alenia Space



International Space Station – Boeing Integrated Defence



ACTS Antenna - NASA



CALIPSO spacecraft -Thales Alenia Space

Herschel -ESA

esa structures European Space Agency

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Case study : NASA

Space systems integrator

NASA and its subcontractors have chosen VA One as a preferred tool for the Moon, Mars and Beyond program (one of the world's largest aerospace projects). The FE, BEM and Hybrid modules of the software are being used extensively in the design of the new ARES launch vehicle and the Orion Crew Vehicle.

"Boeing Integrated Defense has been a long term and successful AutoSEA2 user, and now the capability of … all of the common vibro-acoustic analysis techniques in a single software package. The combined tools provide an efficient analysis environment when performing analysis to support space shuttle and International Space Station requirements. VA One is a standard software tool for Boeing Integrated defense."

Ed O'Keefe, Associate Technical Fellow.
Boeing Integrated Defense

"VA One is intuitive and straightforward to use. I was able to complete a detailed coupled Boundary Element analysis the first time that I used the code"

Jeffrey Larko, Aerospace Engineer
Structural Dynamics, NASA
GLENN Research Center

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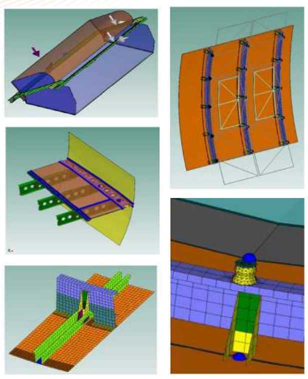
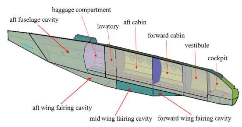
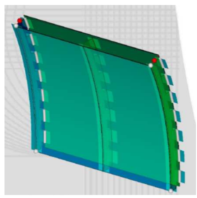
Examples in aircraft



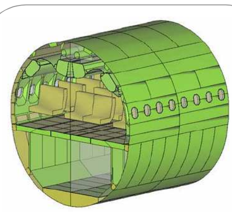
Advanced modeling of aircraft Noise
Boeing, NASA, ESI



Hawker Horizon aircraft –
Raytheon Aircraft Company



FE/SEA and EFM modeling of sidewall - EADS



Aircraft Fuselage Section –
Boeing

NASA BOEING EADS Raytheon Aircraft

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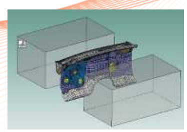
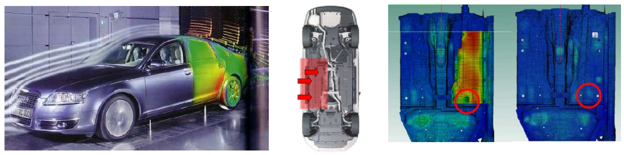
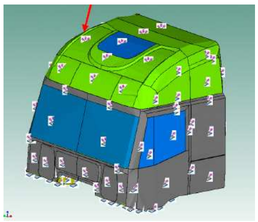
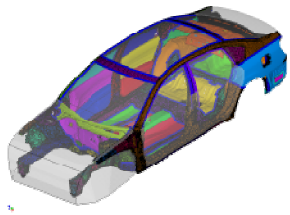
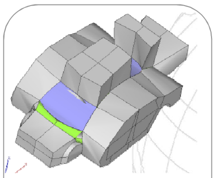
Examples in automotive


Dash TL – General Motors


Windnoise cover design – AUDI, TUM, ESI


Cab Acoustic Comfort - IVECO


FE/SEA structureborne prediction - Nissan


External sound field – Opel, Arrk

IVECO NISSAN GM Audi OPEL ARRK Technical Services

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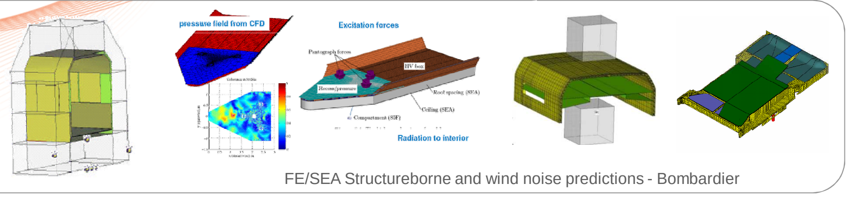
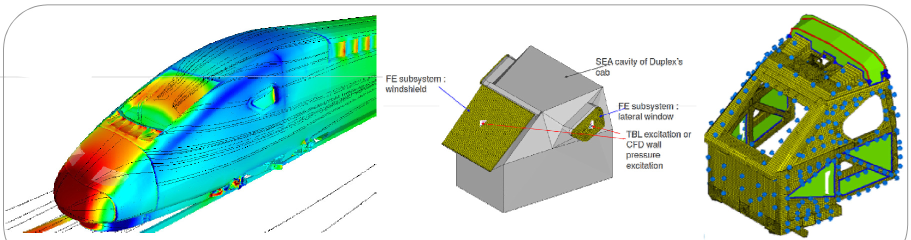
Examples in train



FE/SEA Structureborne and wind noise predictions - Bombardier



FE/SEA structureborne and windnoise predictions - Alstom

BOMBARDIER ALSTOM

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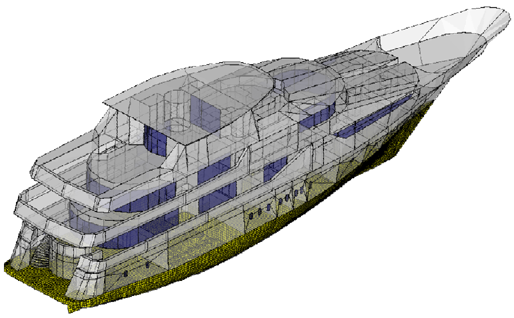

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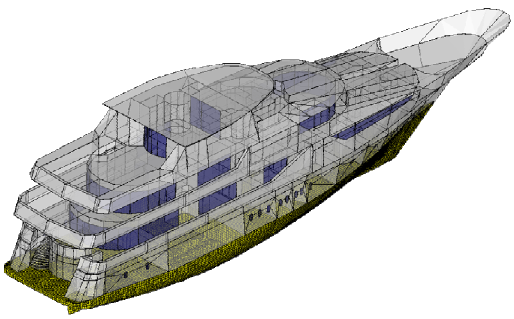

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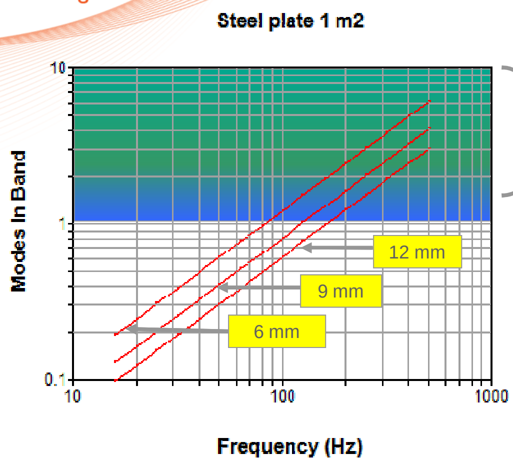
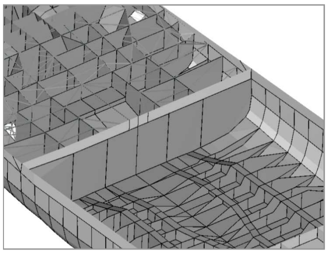
Why "FE/SEA Coupled" for ships



SEA valid zone starts around 100 Hz for a typical steel panel of 1 m²



At frequencies below 100 or 200 Hz, SEA variance on predicted response increases significantly. FEM is more adapted to represent the dense panel network of the lower part of the hull and engine foundation

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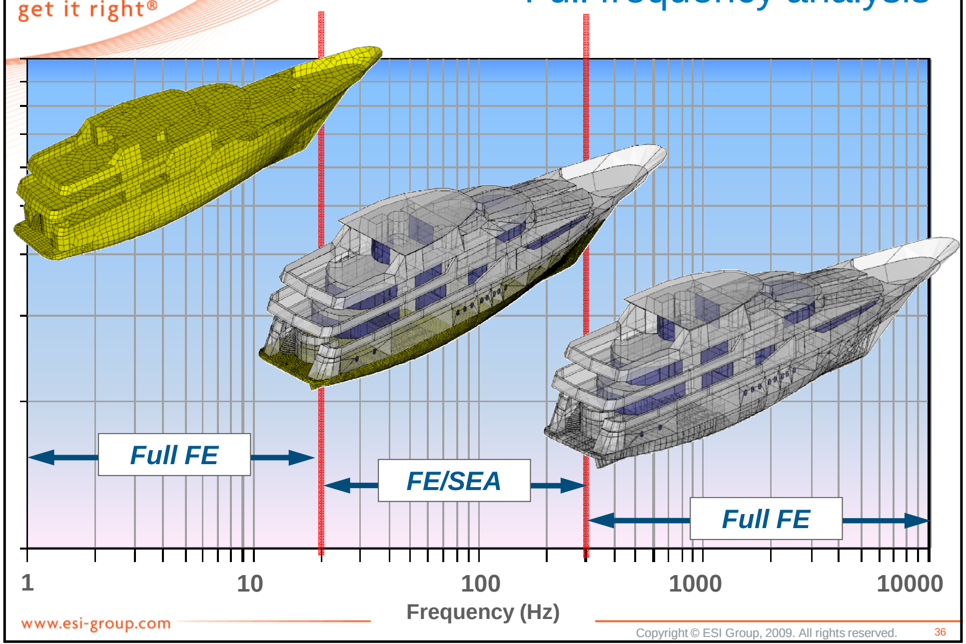
Full frequency analysis



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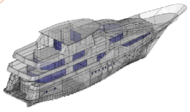
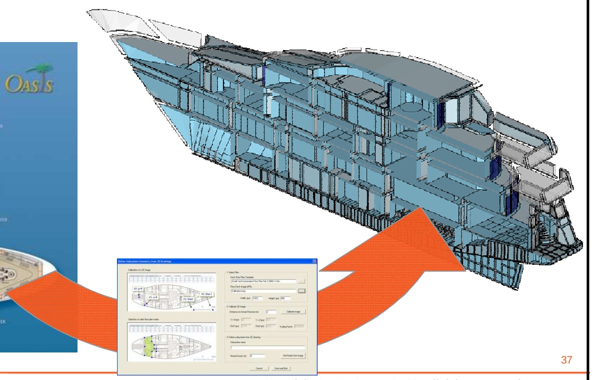


Building SEA model

- Lower part of hull:
  - Use existing FE model or frame section drawings
- Cabins and superstructure:
  - Use general arrangement layout drawings



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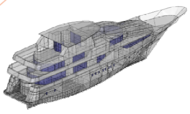
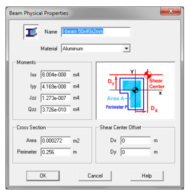
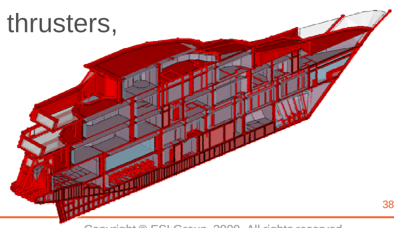


Building SEA model

- Define beam cross-sections to apply to ribbed structural panels such as hull plating and bulkheads
- Create cavities (cabins, tanks...)
- Define acoustic insulation package
  - Based on insulation plan
- Apply fluid loading on hull plating
- Define excitations
  - Engines, gearbox, generators, bow thrusters, air conditioning, propeller noise ...
- Create connections between all subsystems





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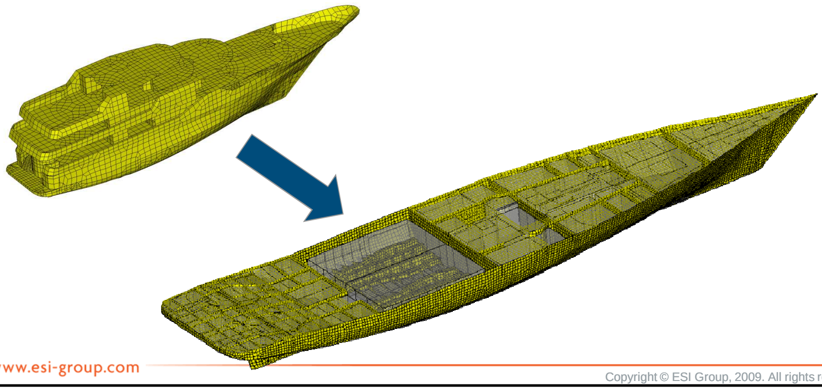
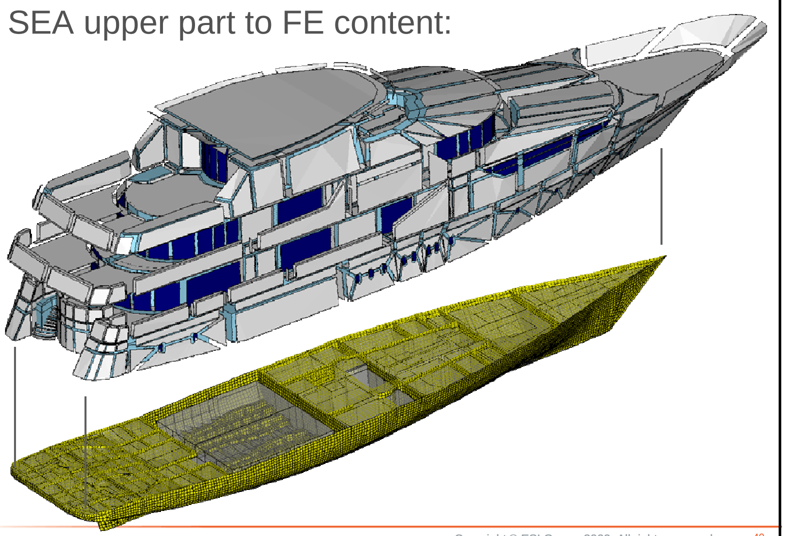
Building “FE/SEA Coupled” model

- FE Content:
  - Use existing FE from bottom to Lower deck floor (~Waterline).
  - Increase mesh density to allow structural analysis up to 200 Hz
  - Automatically create SEA cavities



Building “FE/SEA Coupled” model

- Stitch SEA upper part to FE content:



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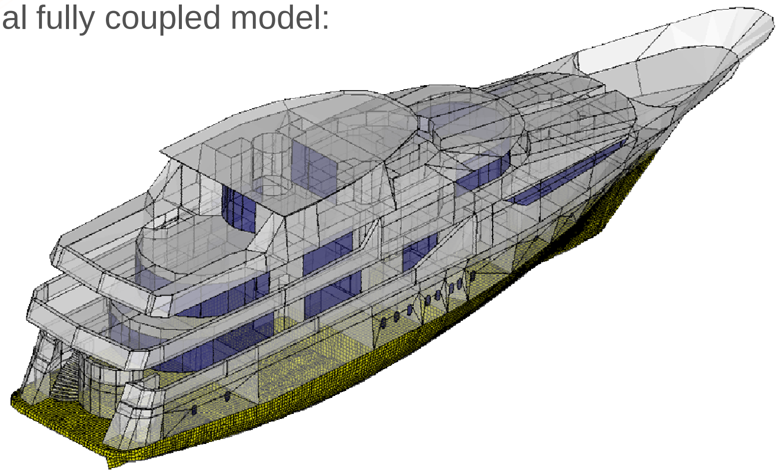
Building “FE/SEA Coupled” model

- Final fully coupled model:



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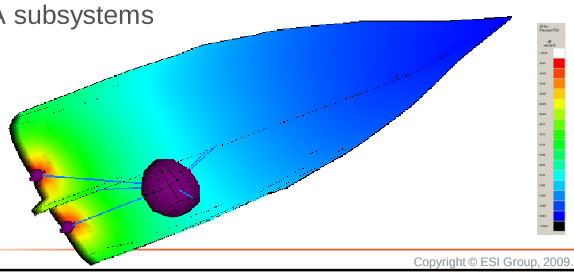
Propeller noise

- Objectives:
  - Determine pressure at wetted hull surface due to propeller noise
  - Use this pressure as an additional source in full SEA and on the FE hull of the “FE/SEA Coupled” model
- Method:
  - BEM FMM to compute propagation of acoustic waves around hull
  - Pressure can be projected on FE modes or average and applied on SEA subsystems



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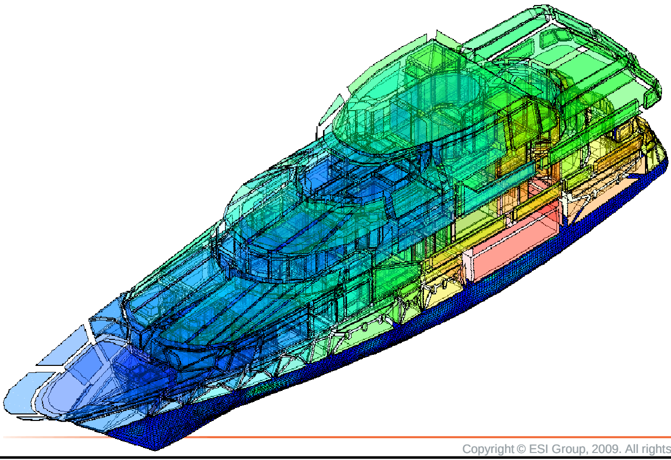
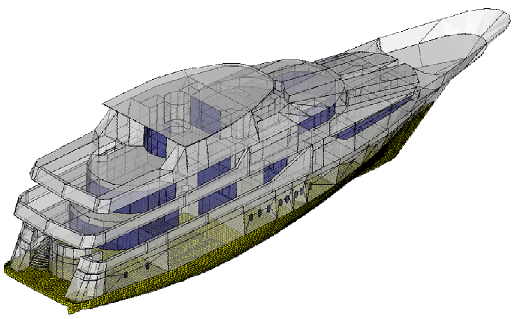
Coupled response computation

- After defining all sources (structureborne, airborne and waterborne) the model can be solved



Outline

- Context
- Introduction to FE/SEA Coupled
- Examples in aerospace, automotive, rail application
- Examples in marine sector
- Conclusion



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Outline

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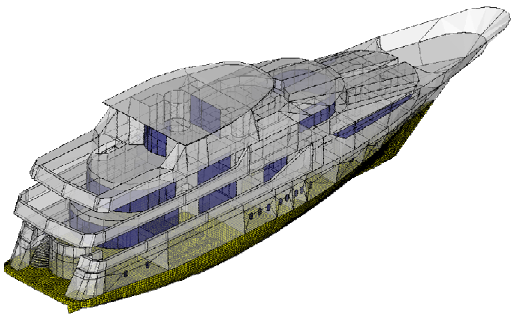

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Conclusion

- "FE/SEA Coupled" enables computation of airborne and structureborne noise at mid-frequency
  - bridging the gap between full FE and full SEA
- "FE/SEA Coupled" is an efficient industrial solution
  - Evidence from diverse industry sectors
- "FE/SEA Coupled" enables user to choose how to represent the structure and fluids
  - Deterministically (FEM, BEM, FMM)
  - Statistically (SEA)
- And couples these methods together into a single solve

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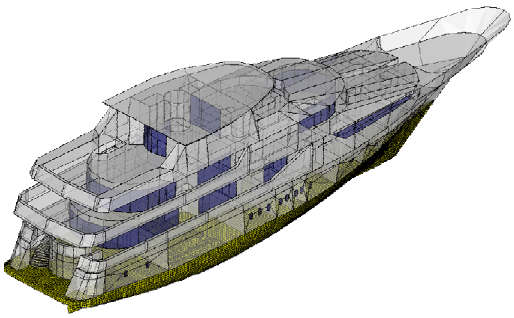
Thank you



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