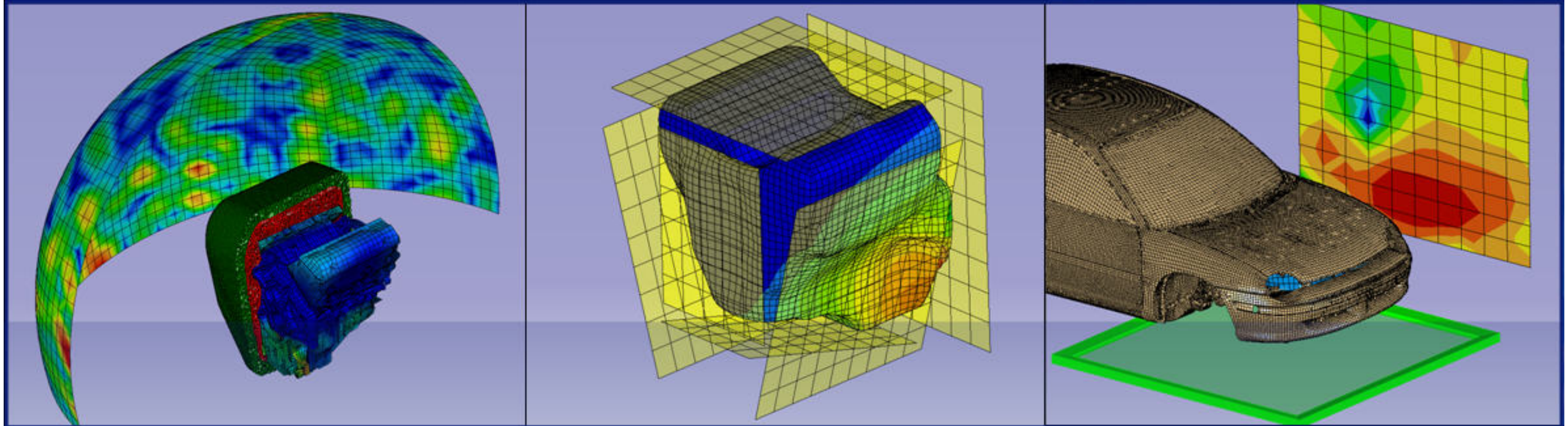

Effect of local mesh refinement on Inverse Numerical Acoustics

Efficiently identify sources for more accurate Engine NVH predictions

Engine EXPO 2010, Stuttgart

Koen Vansant, Product Manager Noise and Vibration Simulation

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Outline

1. *Engine Noise Simulation*
2. *Inverse Numerical Acoustics to Obtain Accurate Surface Vibrations*
3. *Effect of Local Mesh Refinement on Inverse Numerical Acoustics*
4. *Improved Inverse Numerical Acoustic Formulation*
5. *FEM PML – A New Technology for Engine Noise Simulation*

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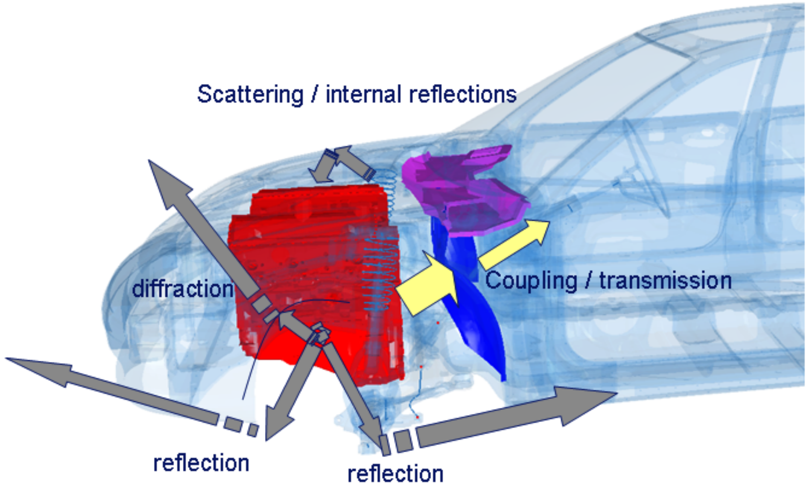
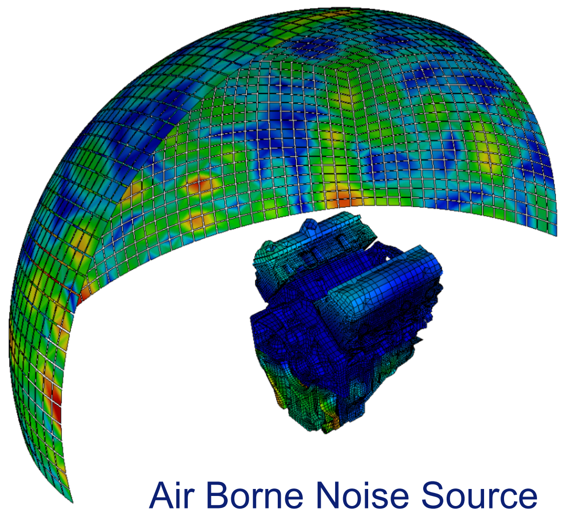
Engine Noise Simulation
Summary of objectives

- Engine Noise can be categorized in:
  - Structure borne:
    - engine mount forces on body → body panel vibrations → interior cabin noise
  - **Air borne**:
    - Exterior: towards outside world (for example pass by noise)
    - Interior: engine as acoustic source causes pressure loading on body panels (firewall) → panel vibration → interior cabin noise



- For air borne noise prediction, both exterior and interior reduction of noise is investigated by
  - Improving transmission loss of body panel in line of sight of the engine source (interior)
  - Acoustic treatments for engine bay panels (bonnet) are tuned (interior / exterior)
  - **Focusing on the source! Reduce Acoustic Power radiated by the engine**



Air Borne Noise Source

Key is to have accurate acoustic prediction of the engine as noise source

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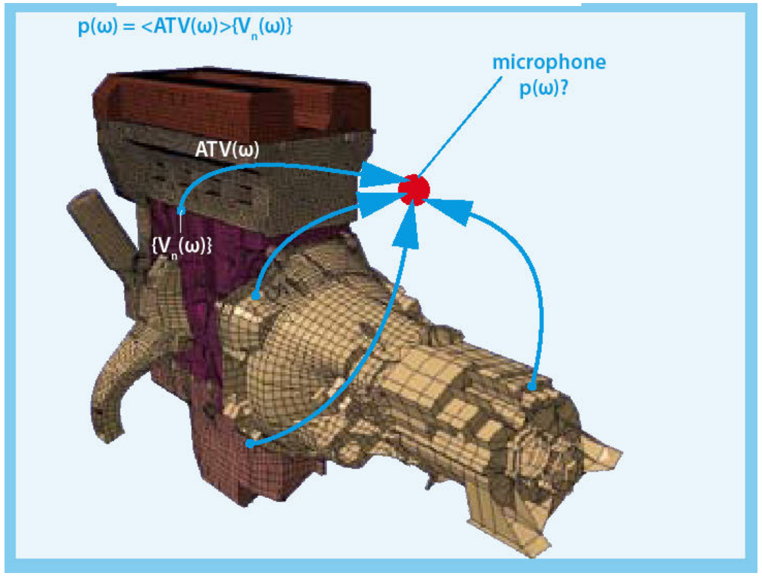
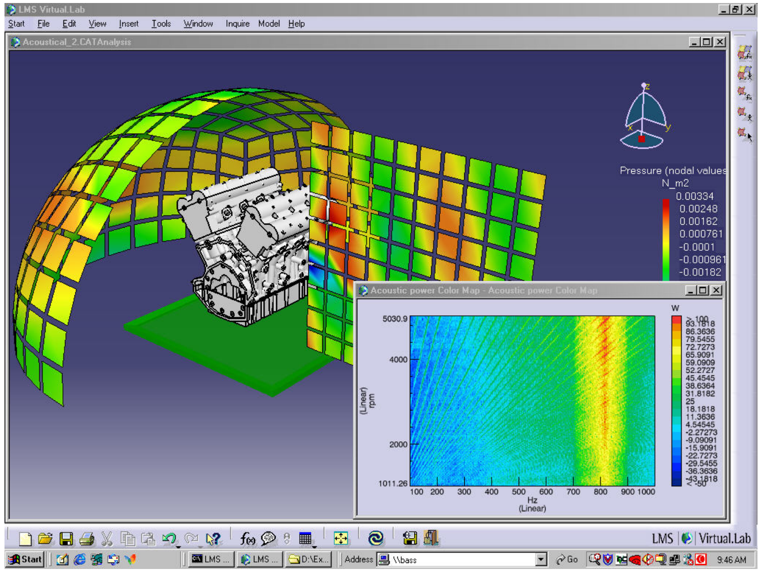
Engine Noise Simulation
Acoustic Transfer Vectors (ATVs)

- ATVs capture the pressure caused by unit normal surface velocity of each acoustic boundary node individually. **Key is that ATVs remain the same for all RPM conditions! ➔** only need 1 larger BEM or FEM computation.
- The actual pressure response (RPM, Hz) = ATV(Hz) x actual surface normal velocities (RPM, Hz)

Based on Acoustic Model, less uncertainty	Typically based on Structural Model, more uncertainty
$p_F = [ATV]_{1,N} \cdot \{v\}_{N,1}$	$\{p_F\}_{NF,1} = [ATV]_{NF,N} \cdot \{v\}_{N,1}$





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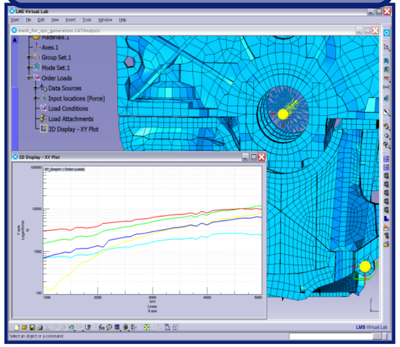
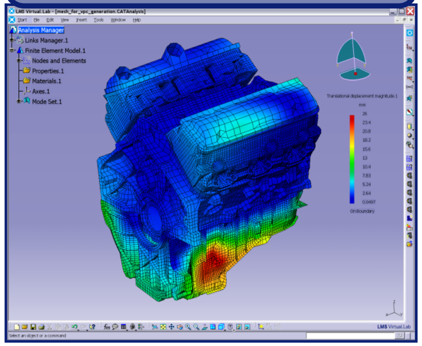
Obtaining Accurate Surface Vibrations
Structural FE approach

Force or Vibration Loads



X

Modal Model



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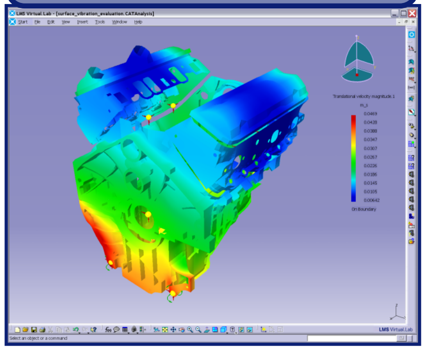
Vibration Response



Standard Procedure

- Structural FE Model of the Engine to compute Real Modes
- Generate Frequency Domain Forces ➔ Waterfall of Frequency Spectra
  ➔ Orders
  Typically from time signals + DSP
- Apply uniform Modal damping
- Compute Forced Vibration Response on the Engine's Surface

Uncertainties

- Local Damping (e.g. layer between oil pan and main engine block) → Modal Approach OK to describe engine operational behavior
- Damping of the Structural Modes → uniform?
- Load application points and load distribution towards structure via RBE
- Load Amplitude / Phase itself
- Temperature effects
- Mass effect of oil distribution

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Outline

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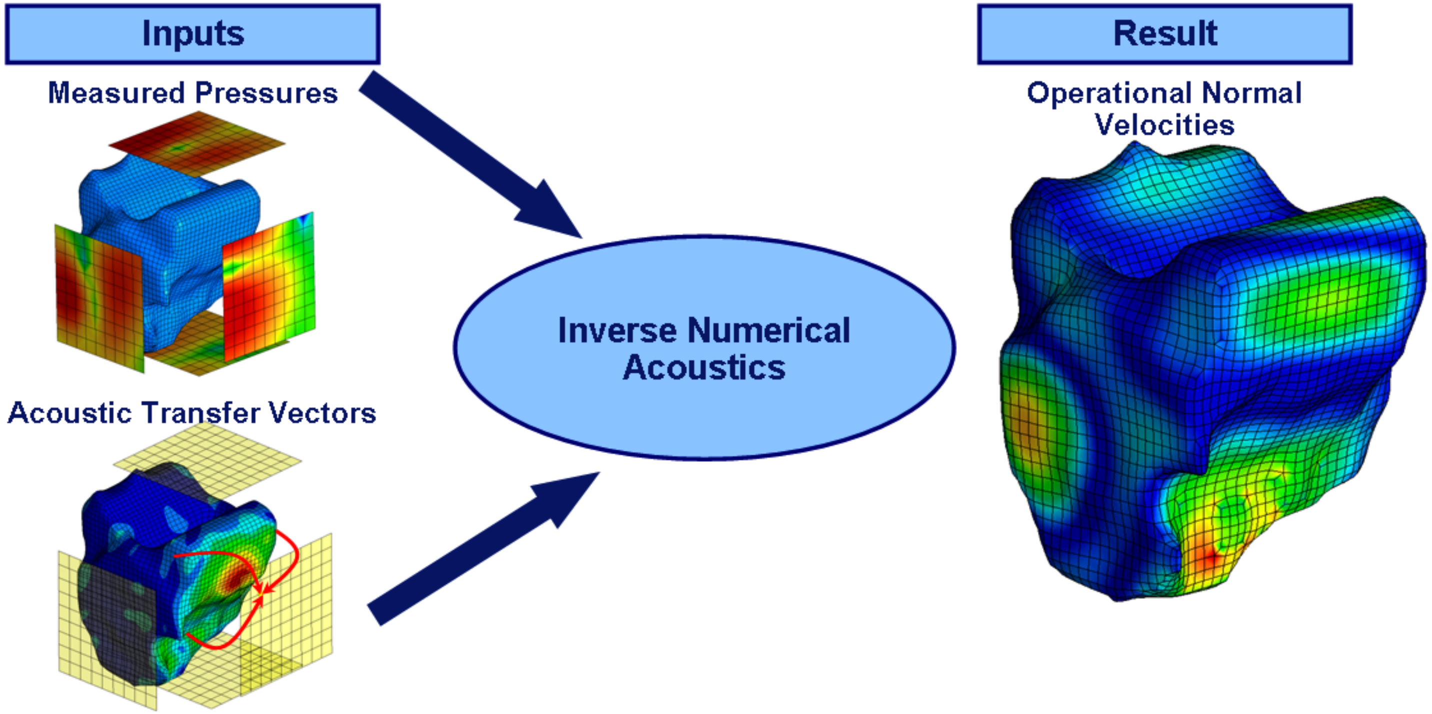
Obtaining Accurate Surface Vibrations
Inverse Numerical Acoustics (INA) approach

- Inverse Numerical Acoustics = Identification of Normal Velocities on a sound radiating surface by using near field Pressure measurements and Acoustic Transfer Vectors

Based on Test data, no uncertainty	Based on Acoustic Model, less uncertainty

- No need for structural FE model → no more uncertainty about loads, structural modes, damping, …
- **Only the topology of the surface needs to be (approximately) captured!**



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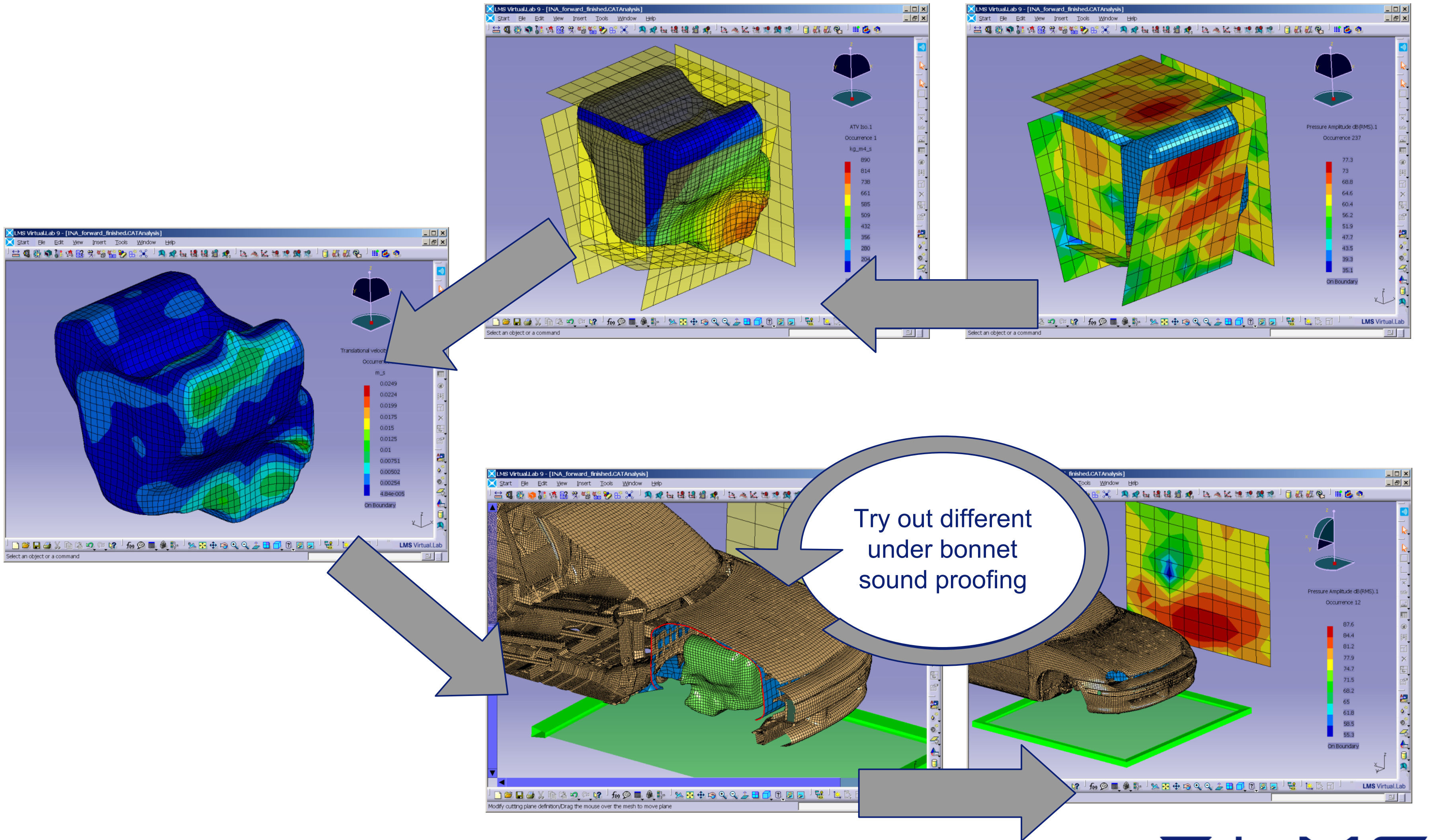
Noise Containment Example using INA

Inverse Numerical Acoustics



Forward BEM ATV Analysis

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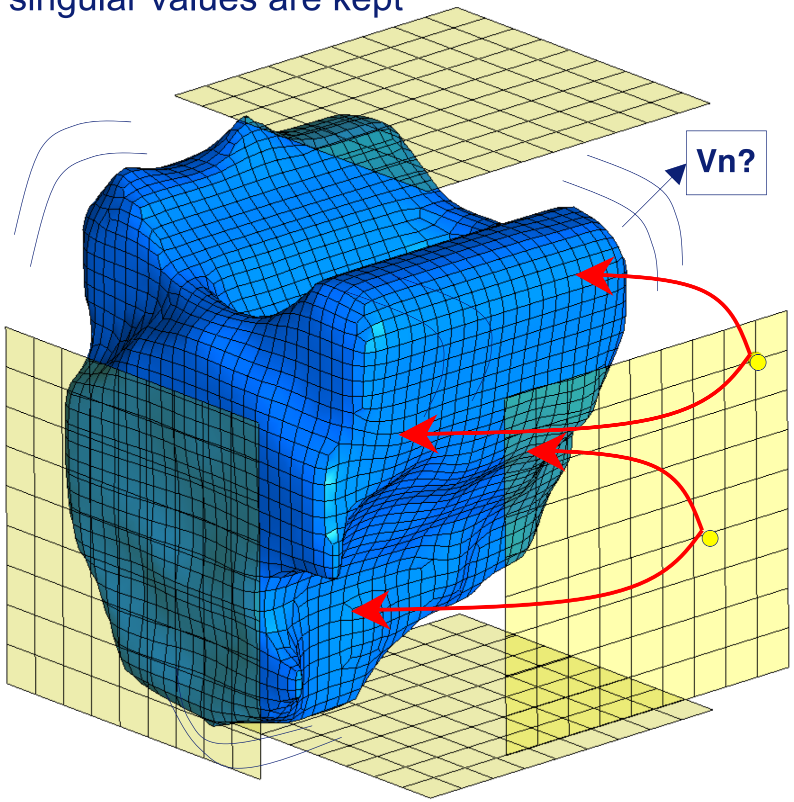
Inverse Numerical Acoustics
Typical Setup using Near Field Operational Pressures

- The equation for the inverse problem is easily derived. HOWEVER, as M (# microphones) will be typically smaller than N (# surface nodes), we must solve an **<u>underdetermined</u>** problem for Vn
  ➔ <u>infinite number of solutions !?</u> Solution will depend on:
  - How the inversion of the ATV matrix is done
  - Choice of microphone point positions
- Using the Moore Penrose Inverse we obtain the unique solution that minimizes the 2-norm for Vn
- Using Singular Value Decomposition (SVD) of the ATV matrix results in the Moore Penrose solution, if all singular values are kept



$$[p]_{mx1} = [ATV]_{mxn} \cdot [v_\perp]_{nx1}$$

↓

$$[ATV]^+_{nxm} \cdot [p]_{mx1} = [v_\perp]_{nx1}$$

$$[V]_{nxn} \cdot [\Sigma]^+_{nxm} \cdot [U]^T_{mxm} [p]_{mx1} = [v_\perp]_{nx1}$$

Inverse Numerical Acoustics
ATV matrix inversion

- SVD Approach:
  - Using all singular values: min $\left\| v_\perp \right\|_2$ solution, but physically OK ??
    - smallest singular values:
      - → big after inversion, dominating the solution
      - → their corresponding singular vectors have a noisy appearance
    - **➔ total solution will have a noisy and non-physical appearance**
  - Truncating the singular value matrix ➔ new, smaller min $\left\| v_\perp \right\|_2$ solution, physically OK
    - By removing the smaller singular values the solution for Vn becomes more smooth
    - Truncation is done by choosing a regularization tolerance, affecting the matrix condition number
    - By truncating the singular values we take away (a small amount of) information ➔ How to choose the regularization tolerance ??

$$[V]_{nxn} \cdot [\Sigma]^{+}_{nxm} \cdot [U]^{T}_{mxm} [p]_{mx1} = [v_\perp]_{nx1}$$

$$[\Sigma]^{+}_{nxm} = \begin{bmatrix} \sigma_1^{-1} & & & & \\ & \sigma_2^{-1} & & & \\ & & \sigma_3^{-1} & & \\ & & & \ddots & \\ & & & & \sigma_m^{-1} \\ & & & & \end{bmatrix}$$

Regularization tolerance

$$\frac{\sigma_i}{\sigma_{\max=1}} < \alpha \Rightarrow \not\sigma_i$$

$$\kappa(ATV) = \frac{\sigma_{\max}(ATV)}{\sigma_{\min}(ATV)} \le \alpha^{-1}$$

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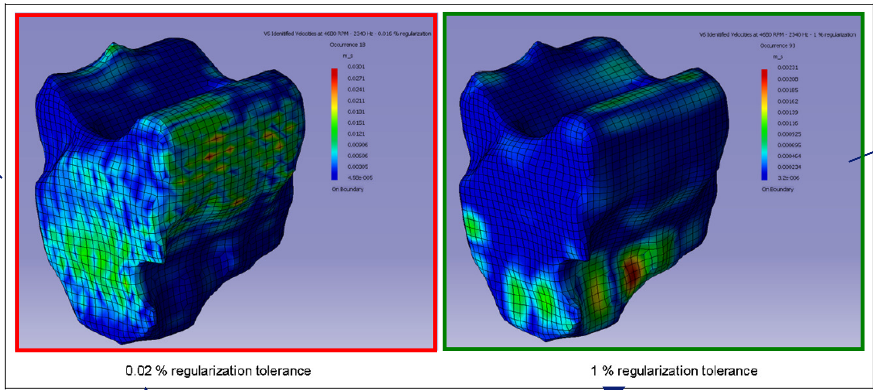
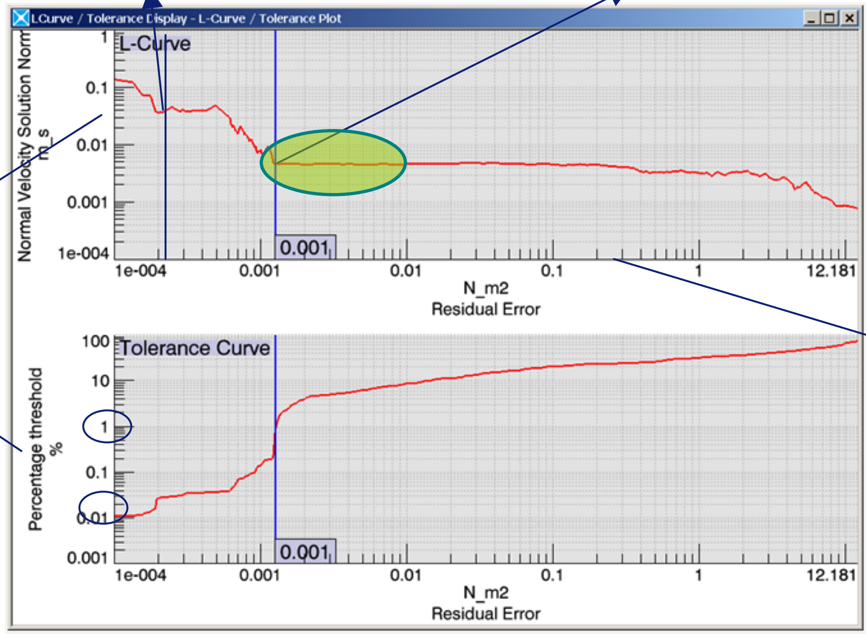
SVD truncation – The L-curve

- Closer to purely mathematical (Moore Penrose) solution, low truncation
- Near field pressures can be reconstructed: very small error
- but solution is noisy, not very physical

Indentified normal velocities at 4680 RPM, 2340 Hz, 0.02 % regularization tolerance (left), 1 % regularization tolerance (right)



- More physical solution, higher truncation → more small singular values removed
- Near field pressures can be reconstructed with still only a small error
- solution is physically meaningful



- 2-norm of Vn: measure of 'noise' on the solution

- Regularization threshold

- Error between measured near field pressures and reconstructed near field pressures (using the identified surface velocities)

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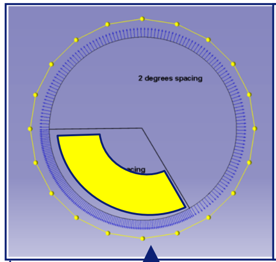
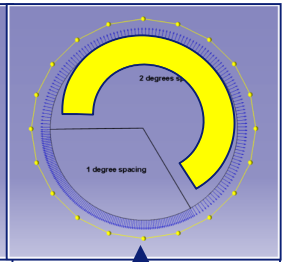
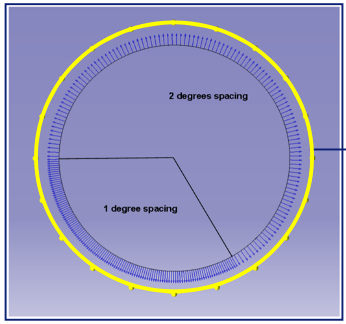
ATV matrix at 1000 Hz for a radiating ring structure

- Smaller elements → less acoustically effective → lower ATV values
- For a fixed field point → more surface nodes are seen and do contribute



- Larger elements → more acoustically effective → higher ATV values
- For a fixed field point → less surface nodes are seen and do contribute





20 microphone points

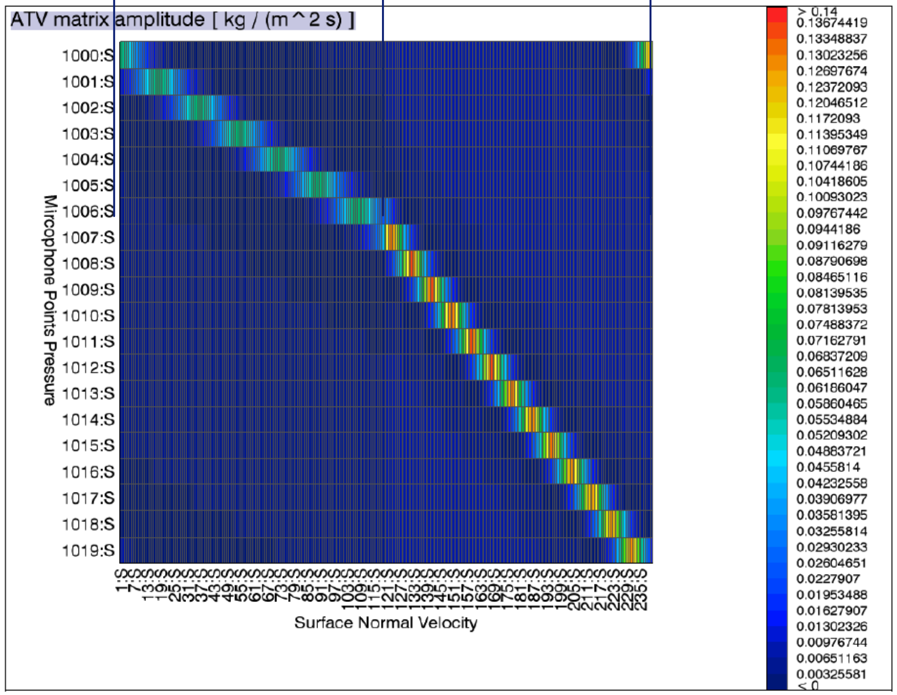


Fig 6. Ring structure ATV matrix amplitude at 1000 Hz

- Ring structure results in a very well conditioned ATV matrix: rows almost linearly independent
- This means that the pressure in a field point is almost completely defined by the nearby surface nodes

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Radiating Ring Structure Solution

- For the ring structure, the pressure in a microphone point can be approximated using the r nearest surface nodes and an ATV vector of size 1 x r :

$$p_{1x1} = \left[ATV_{p,1} \quad ATV_{p,2} \quad \cdots \quad ATV_{p,r} \right]_{1xr} \cdot \begin{bmatrix} v_{\perp 1} \\ v_{\perp 2} \\ \vdots \\ v_{\perp r} \end{bmatrix}_{rx1}$$

- The equivalent inverse problem for the r nearest surface nodes (Moore-Penrose inverse):

$$v_{\perp i} = p \cdot \left(\frac{ATV^{*}_{p,i}}{\sum_{k=1}^{r} ATV_{p,k} \cdot ATV^{*}_{p,k}} \right)$$

- The average velocity is inversely proportional with the ATV magnitude → OK, as expected
- The individual velocity is proportional with the ATV magnitude
  - Depending on the distance ring surface, microphone point → OK
  - **<u>Depending on Element Size ?</u> ➔ A larger element has a higher ATV → NOK! We would like the INA solution to be independent of the surface discretization**

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Radiating Ring Structure Improved Solution

- Solution to attenuate the effect of local mesh refinement:
  - Reformulate the inverse problem using scaling factors Si for ATVs
  - include a condition that if the **pressure / velocity relations = ATV/nodal area (Ai)** are equal for all surface nodes, the velocity should be equal for all surface nodes ←→ **pressure / volume velocity**

$$\left.\begin{array}{l} p_{1x1} = \begin{bmatrix} \dfrac{ATV_{p,1}}{S_1} & \dfrac{ATV_{p,2}}{S_2} & \cdots & \dfrac{ATV_{p,r}}{S_r} \end{bmatrix}_{1xr} \cdot \begin{bmatrix} S_1 v_{\perp 1} \\ S_2 v_{\perp 2} \\ \vdots \\ S_r v_{\perp r} \end{bmatrix}_{rx1} \\ \forall i, \dfrac{ATV_{p,i}}{A_i} = \dfrac{p}{v_{\perp i} \cdot A_i} = C \quad \Rightarrow \quad v_{\perp i} = v_{\perp} \end{array}\right\} \Rightarrow \forall i, S_i = \sqrt{A_i}$$

- New formulation to be tested: $[p]_{mx1} = [ATV]_{mxn} \cdot [\grave{S}]_{nxn} \cdot [\grave{S}]^{-1}_{nxn} \cdot [v_{\perp}]_{nx1}$

$$[\grave{S}]_{nxn} \cdot [sATV]^{+}_{nxm} \cdot [p]_{mx1} = [v_{\perp}]_{nx1}$$

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Radiating Ring Structure Solution
Comparison between scaling factor choice

$$[S] = \begin{bmatrix} \ddots & & 0 \\ & 1/A_i & \\ 0 & & \ddots \end{bmatrix}$$

$$[S] = \begin{bmatrix} \ddots & & 0 \\ & 1/\sqrt{A_i} & \\ 0 & & \ddots \end{bmatrix}$$

$$[S] = I$$

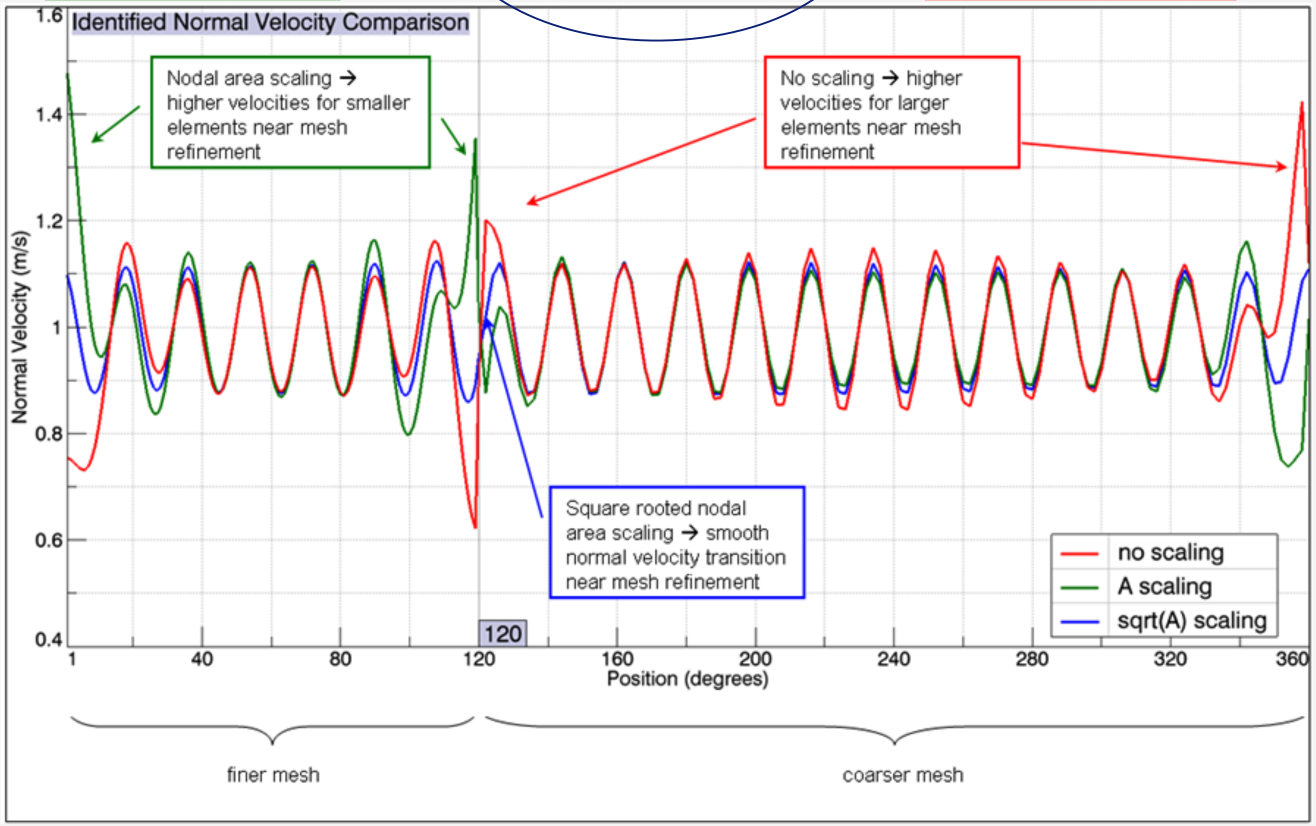

Fig 8, the effect on identified normal velocities for different scaling approaches in case of mesh refinement

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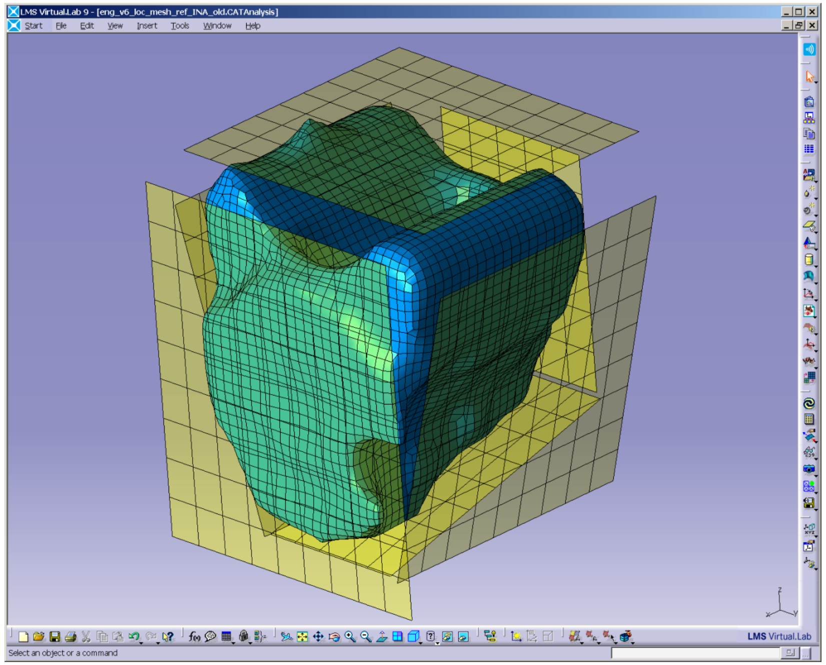
New INA formulation – Test on industrial problem

- New formulation for INA was derived based on the ring structure model:
  - 2d problem
  - Almost ideal ATV matrix to start with → almost independent ATV rows
- How will the new formulation perform for real sized 3D problems
  - Engine model: 500 → 2500 Hz
  - With / without imposed mesh refinement



engine model	
nr microphone points near field	496
nr microphone points far field	9
nr of BEM nodes	3971
frequency	500 - 2500 Hz
distance between near field microphone points	70 mm
average distance to surface	55 mm
smallest λ/2	68 mm
smallest λ/3	45 mm

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Engine Case 1
No imposed mesh refinement

- Although the mesh size appears quite homogeneous, some variation in mesh size exists …
- Procedure:
  - Known velocity field applied at the engine surface (FE simulation)
  - Predict the near field pressure response
  - Identify the surface velocities using INA and compare with original.
  - Compare also far field pressure real vs reconstructed
- **Results show improved correlation (about 0.1 higher) even for this BEM mesh with rather uniform mesh size!!**
- Far field pressure was well predicted for both INA with and without preconditioning

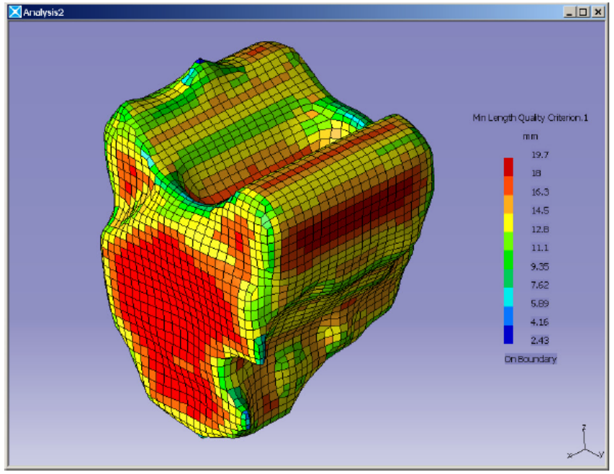

Fig 16. Different element sizes in the generated wrapped engine BEM mesh

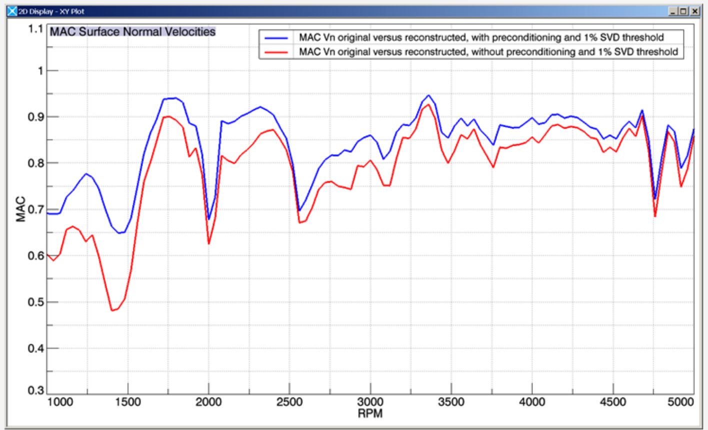

Fig 19. MAC between actual and reconstructed surface normal velocities, with preconditioning (blue) and without preconditioning (red)

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Engine Case 2
Imposed mesh refinement

- Analysis was redone but with a new BEM mesh that included a local mesh refinement for the oil pan ➔ Results show again better correlation for Vn using the INA formulation with preconditioning
- The velocity solution for both INA approaches allowed to predict accurately the sound in the far field
- However for Source Localization, the new preconditioned INA approach is advised as provides better results near at the boundary between mesh domains with different mesh size

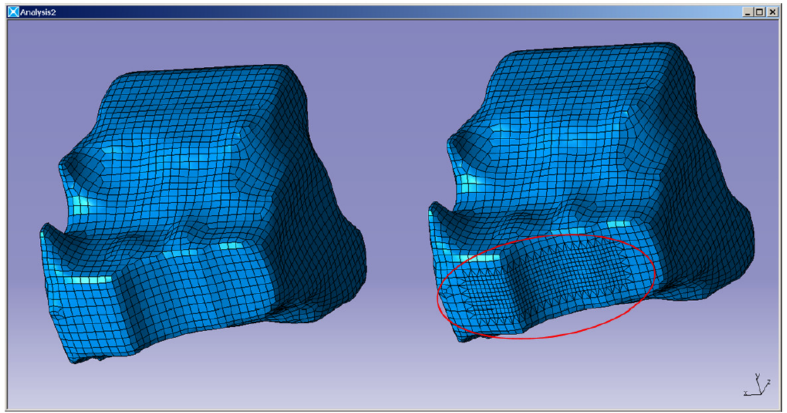

Fig 20. Setup for the Engine BEM model with local mesh refinement

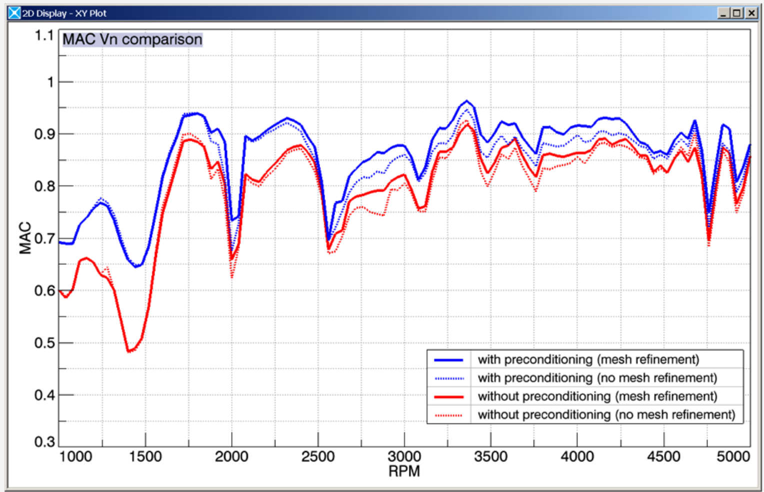

Fig 23. MAC between actual and reconstructed surface normal velocities, with preconditioning (blue) and without preconditioning (red). The dotted line curves represent the MAC results for the BEM model without mesh refinement

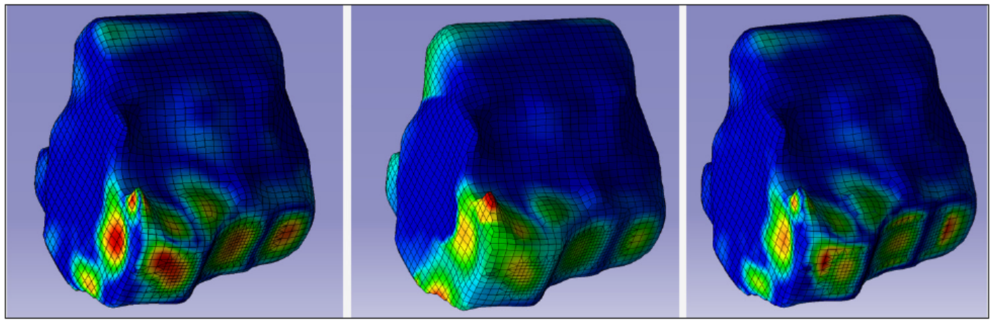

Fig 24, comparison of surface normal velocities at 3160 RPM: with preconditioning and 1 % regularization threshold (left), original (middle), without preconditioning with 1 % regularization threshold (right)

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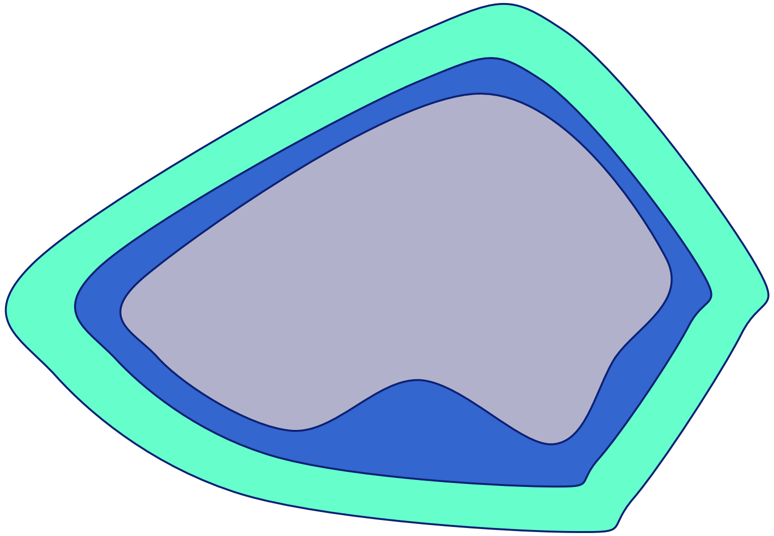
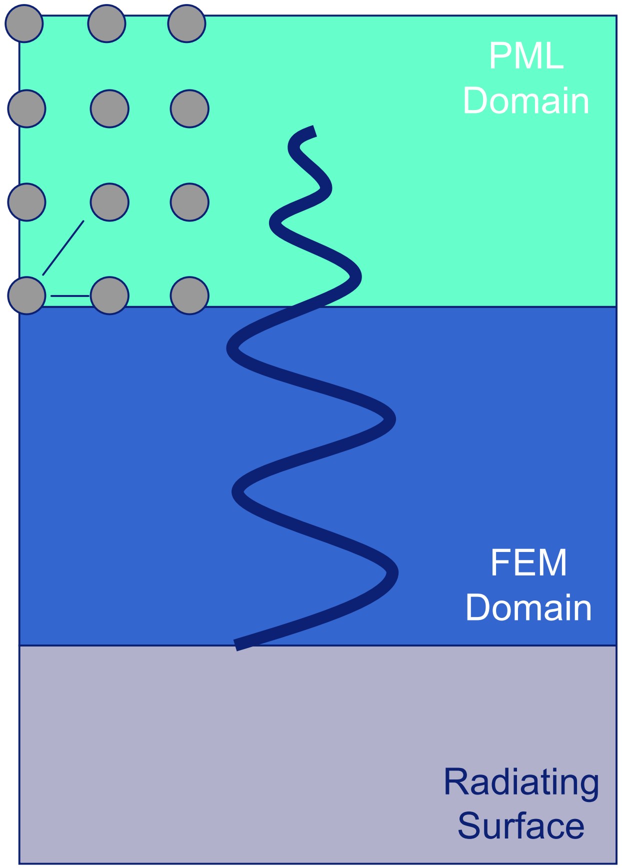
FEM for exterior acoustics : New approach
PML (Perfectly Matched Layer)

- A new approach, called **PML**, to perform fast exterior simulation using FEM Models:



The model is made of :

1. A radiating Surface
2. A convex FEM domain
   - corresponding to the fluid (e.g. Air)
3. A convex PML domain
   - Will absorbe the waves to meet the Sommerfeld condition



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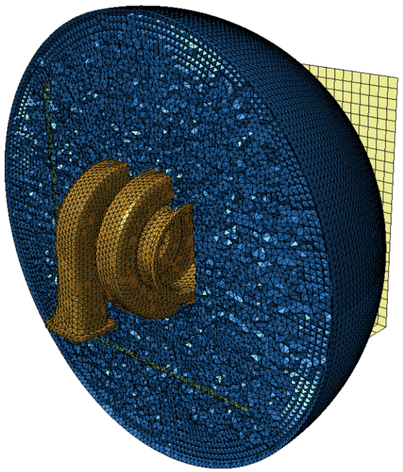
FEM for <u>exterior acoustics</u>
Noise Radiated by a turbo charger

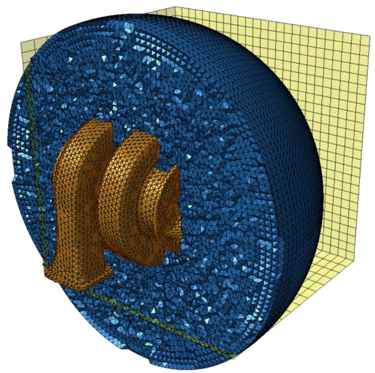
Rho C BC



 # nodes: 478 kNodes

XL model

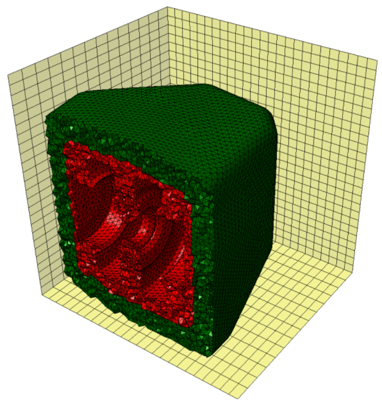
IFEM



 # nodes: 121 kNodes

L model

PML



 # nodes: 79 kNodes

S - M Model

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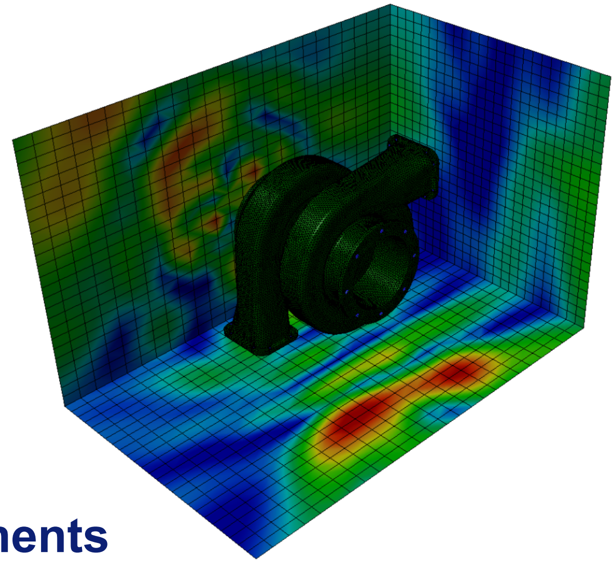
Comparison on a small turbocharger radiation model

exterior acoustics comparison

LAPTOP	LAPTOP	TUX4	TUX4
1024 RAM	2048 RAM	12 000 RAM (2 x 6000)	12 000 RAM (1 x 12000)
1 * PROC Intel 2.79 GHz	1 * PROC Intel 2.79 GHz	2 * PROC Intel Xeon 2.66 GHz	1 * PROC Intel Xeon 2.66 GHz

6 frequencies (9.8 - 10 kHz)	FEM	IFEM	FEM PML	indir BEM
# nodes	477 990	121 387	**34 525**	5 986
# elements	2 816 483	692 652	176 501	11 968
# ifem nodes	x	8 666 (order 3)	x	x
# ifem faces	x	17 328	x	x
# pml nodes	x	x	49 446	x
# pml elements	x	x	259 441	x
# total nodes	**477 990**	**121 387**	**79 035**	**5 986**
# field points	1951	1951	1951	1951
RESULTS				
accuracy				
correlation with BEM	0.97	0.93	0.96	1
timing				
direct (min/f)	x	**42.0**	**5.2**	**6.2**
iterative (min/f)	**1.6**	**2.3**	**0.4**	
direct fem perf factor vs BEM	x	**0.1**	1.2	
iterative fem perf factor vs BEM	3.9	2.7	15.5	



VL Rev 9
Tremendous performance improvements
Using PML + new Iterative Solver

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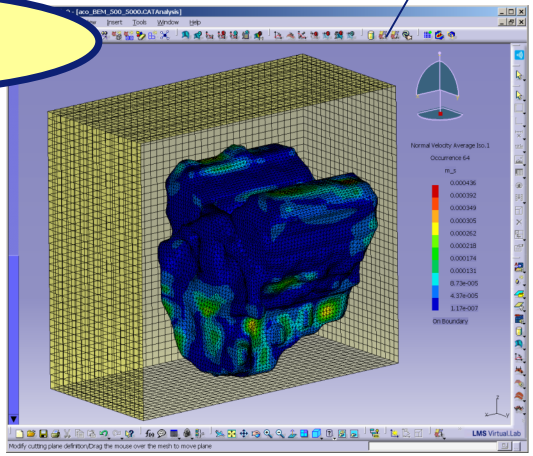
Virtual.Lab Acoustic Radiation Simulation
Performance comparison BEM – FEM PML

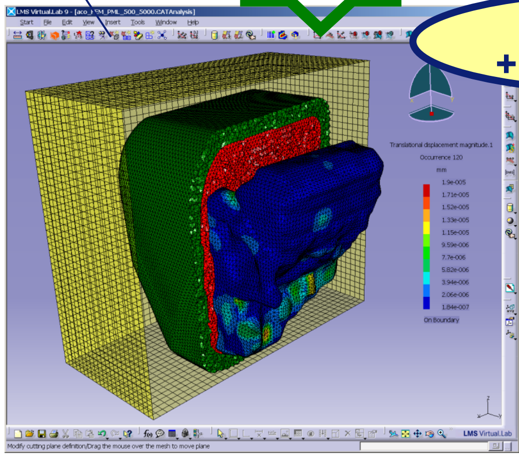
Acoustic Radiation Simulation [0.5-5kHz] for Engine Model (12500 boundary nodes)

Results	BEM	FEM PML iterative	Performance ratio FEM PML / BEM
Memory used	12 GB	15 GB	
# processors used	2	4	
CPU Time (minutes)	1560	112	
Number of Frequencies Solved	46	109	
CPU Time / Freq (minutes)	33.9	1.0	33.0
CPU Time / Freq per proc	67.8	4.1	16.5

BEM

Nodes:12500
Elements: 25000
Field Points: 9600





FEM PML + iterative solver

Nodes:
- Boundary: 12500
- FEM Model: 95000
- PML Layer: 96000

Elements: 988000
Field Points: 9600

Linux Machine info	
number of processors available	8 x 2.8 HGz
memory available	16 GB

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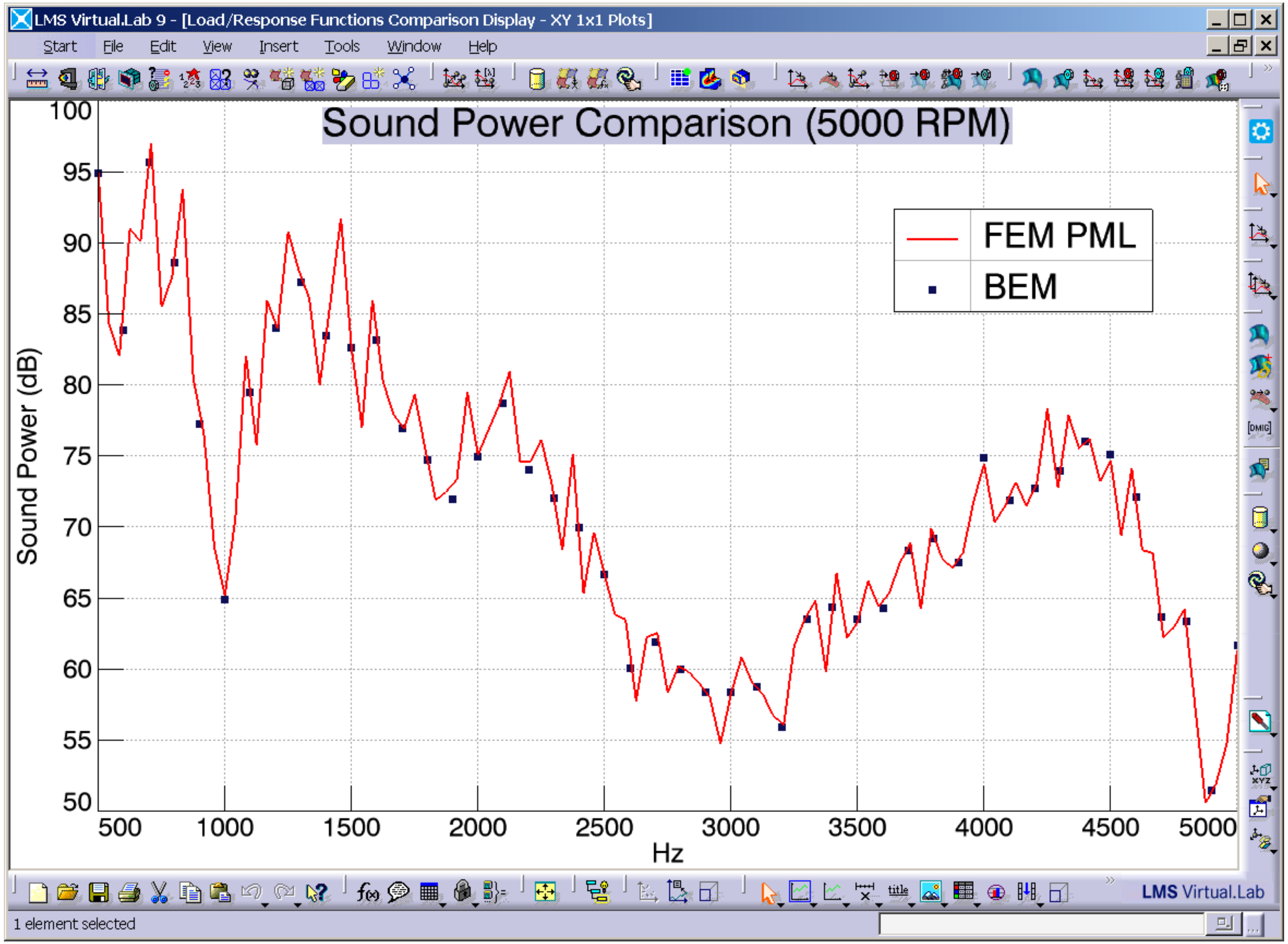
Virtual.Lab Acoustic Radiation Simulation

Accuracy comparison BEM – FEM PML



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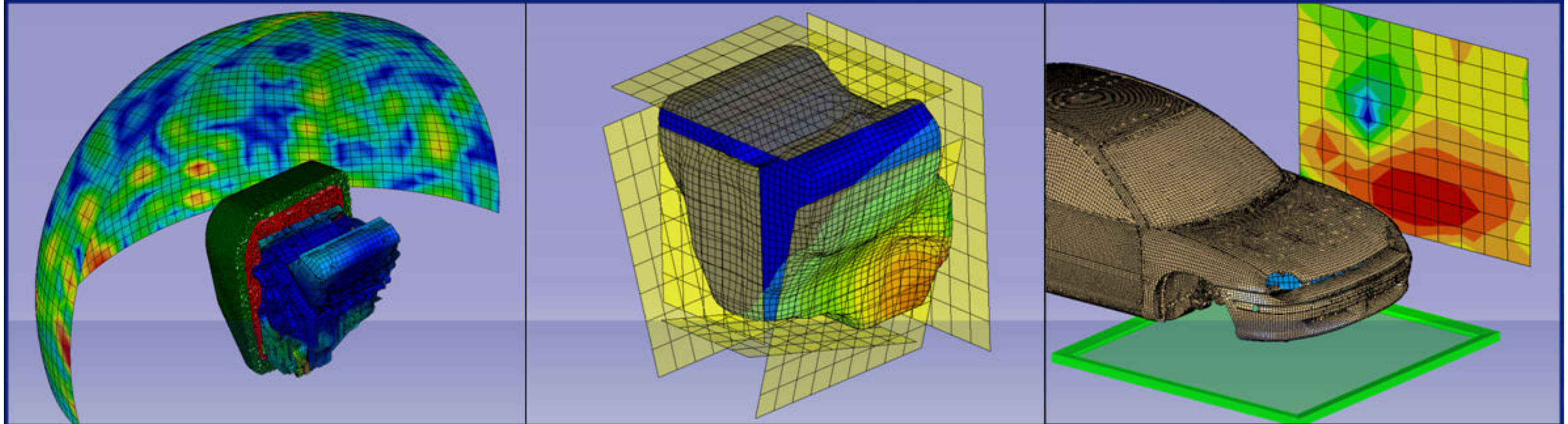

Effect of local mesh refinement on Inverse Numerical Acoustics

Efficiently identify sources for more accurate Engine NVH predictions

Engine EXPO 2010, Stuttgart

Koen Vansant, Product Manager Noise and Vibration Simulation