Recent Advances in Vibro-Acoustic Modeling & Numerical Solvers for Engineering Applications

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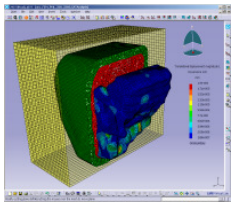
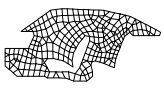
Overview

1. Introduction
2. FEM PML/AML for radiation problems
3. Example on an industrial V6 engine model
4. Conclusions



Introduction

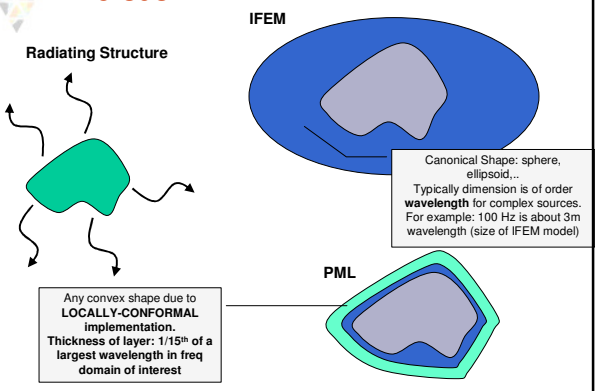
- ***Two primary methods when doing acoustic simulations:***

Finite Element method	Boundary Element method
	
Higher modeling effort	Lower modeling effort
Modal approaches possible	No modal approach
Symmetric matrices	Non-symmetric matrices for DBEM
Heterogeneous fluid	Homogeneous fluid only

Introduction

- ***For radiation problems***
  - With BEM
    - ease of modeling
    - Sommerfeld radiation condition at infinity is guaranteed; no radiated power will be reflected from infinity
  - With FEM
    - More difficult to simulate
    - Need of artificial tools to extend the acoustic domain (e.g. three dimensional volume elements - IFEM)

PML versus IFEM



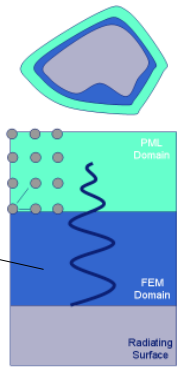
PML - How does it work?

Principle:

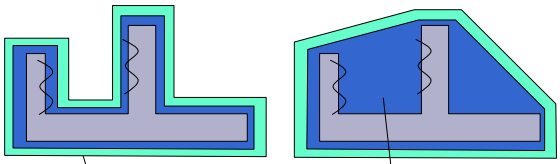
- 2 steps computation:
  1. Solution is computed in the FEM domain considering the PML domain
  2. Solution from first step is used to compute solution at the field points without the PML domain
- PML domain is an absorption area to simulate free field radiation as no reflection happens in the FEM domain
- Field points can be defined out of the domains

Benefits:

- FEM region can be very close to the radiating surface, **1 element is sufficient**, resulting in **much lower number of elements needed**
- Radiating surfaces : **ANY convex shape**
- **Lower bandwidth** and **better conditioning** of the matrix



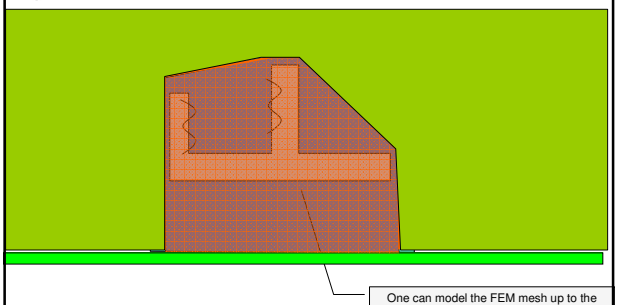
Why should PML be convex ?



Modal behavior could be present between these 2 vibrating parts. With this PML, the modal behavior is lost because all waves are absorbed in the boundary

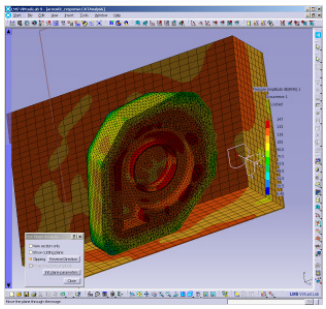
In this case, the modal behavior between the vibrating panels is taken into account accurately.

Perfectly Matched Layer
What about symmetry plane ?



One can model the FEM mesh up to the ground plane (symmetry plane). In the field point calculation, using KIRCHOFF theory, the symmetry plane is taken into account.

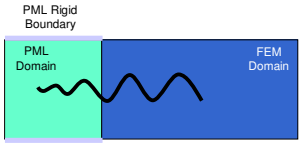
PML: example



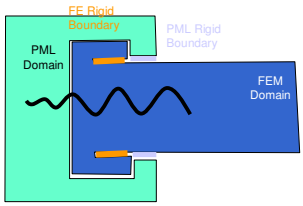
Save potentials to see how well the waves are actually attenuated in PML layer

PML for acoustic propagation in ducts
Modeling principles

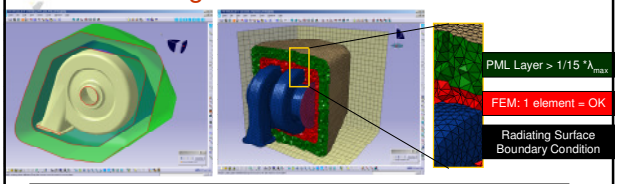
Wave propagation in infinite duct.
Infinite Duct Ending



Wave propagation out of open duct into free field.



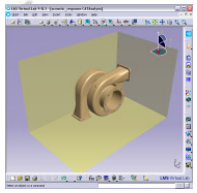
Perfectly Matched Layer
FEM Modeling

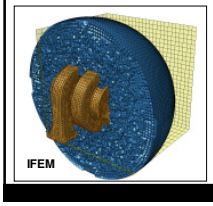


From PML to AML:

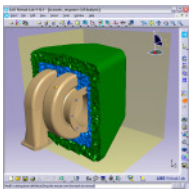
- From **Rev 9**, PML technology is available. The user has to create both FEM and PML layers from the radiated surface.
- The PML layer depends on the maximum frequency. So from **Rev 9SL3** the PML layer will automatically be created by the solver in order to get an optimize layer for each computed frequency line**.** It is called the **AML** technology.
  - New computation time reduction compared to PML
  - Less required memory as the layer is always optimized w.r.t. to the frequency.

AML = Next generation PML
Exterior Radiation: different technologies

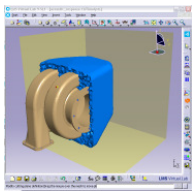




PML

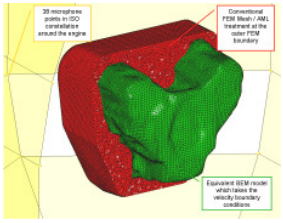


AML



Engine acoustic radiation analysis
Industrial V6 Engine

- ***FEM AML comparison with BEM and FMBEM – No symmetry plane***



Model Overview

- 38 Microphones around the engine
- No symmetry plane
- Frequency Range : 100 to 5000Hz with a step of 10Hz
- Multi-RPM analysis : from 1000 to 5000RPM with a step of 100RPM
- 285 structural modes (including residual flexibility vectors at structural loading points)

Engine acoustic radiation analysis
Industrial V6 Engine

modeling method	Indirect BEM 100-5000 Hz	FEM AML 100-5000 Hz	Factors Time Improvements
# nodes	15,424	154,913	
# elements	30,844	837,482	
# field points	38	38	
Single RPM Acoustic Response	direct	iterative	
# processors	3	8	
time (min)	**589.97**	**3.82**	155
RAM at start (Gb)	22.5	2.65	
RAM steady state (Gb)	22.5	2.65	
# freqs (300-4900 Hz step 200 Hz)	24	24	
equivalent 1 processor time/freq	73.75	1.27	58
ATV computation	direct	direct mumps	
# processors	3	2:4 threads	
time (min)	**3361**	**115**	29
RAM at start (Gb)	22.5	5	
RAM steady state (Gb)	22.5	5	
# freqs (100-5000 Hz step 40 Hz)	**124**	**124**	
equivalent 1 processor time/freq	81.31	1.85	44
Full RPM Modal ATV Response	matrix multiplication	matrix multiplication	
time (min)	9.78	13.5	
delta RAM (Gb)	0.3	0.3	
# freqs (491 Freqs x 41 RPMs)	20131	20131	
time/freq	4.86E-04	6.71E-04	

Machine : Windows 64 bit Dual Quad-Core Desktop (8 cores in total) – 24GB RAM

For normal acoustic response (fixed RPM):

- *Gain of 58 achieved per frequency per processor using iterative solver.*
- *Less memory consumption with iterative solver. More cores can work in parallel to solve multiple frequencies independently at the same time.*
- *So considering also machine's hardware iterative solver can compute the acoustic response at the 38 field points 155 times faster than with Indirect BEM approach.*

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- *ATV:*
  - *ATV FEM PML/AML computed with direct MUMPS solver.*
  - *Computation with 2 processes with 4 threads each (more memory consumption then iterative solver)*
  - *29 times faster than ATV computed with direct BEM approach.*
  - *ATV computed using iterative solver possible but not advised because multi-right side problem => restarts needed as many times as there are field points.*

- For full run-up of 41 RPM's:
  - *No more matrix inversion needed*
  - *Matrix multiplication between ATV and velocity on the skin of the engine.*
    ⇒ extremely fast operation

Engine acoustic radiation analysis
Industrial V6 Engine

- ***ATV computation comparison :***
  - FEM AML using direct MUMPS solver versus FMBEM
  - 1 frequency computed
  - Mesh valid up to 11kHz

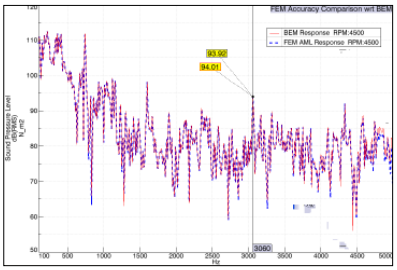
modeling method	FM BEM ATV 8000 Hz	FEM AML ATV 8000 Hz
# nodes	61,690	890,264
# elements	123,376	5,031,654
# field points	38	38
ATV computation	FMBEM iter	DIRECT MUMPS
# processors	4	1,4 threads
time (min):	4005	1392
RAM (Gb):	1,5	18
# freqs (8000Hz, mesh good for 11kHz)	1	1

- **FEM AML with MUMPS solver:**
  - Only 1 process with 4 threads
- **FMBEM:**
  - 4 cores used
- **FEM AML faster** but in case the engine would have been larger, FMBEM approach would likely perform better.

Machine : Windows 64 bit Dual Quad-Core Desktop (8 cores in total) – 24GB RAM

Engine acoustic radiation analysis
Industrial V6 Engine

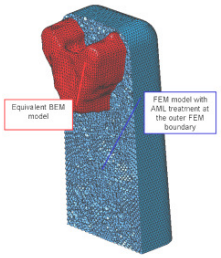
- ***SPL response in 1 of the 38 field points***



Almost identical results with FEM and BEM approaches

Engine acoustic radiation analysis
Industrial V6 Engine

- ***Influence of symmetry plane – Comparison FEM PML/AML using different solvers***



Model Overview

- Same Engine as previously
- With symmetry plane which forces the FEM model to reach up till the ground
- BEM and FEM models valid up to 3kHz
- 22 Microphones around the engine
- Multi-RPM analysis : from 1000 to 5000RPM with a step of 100RPM

Engine acoustic radiation analysis
Industrial V6 Engine

computing method	DIRECT	ITERATIVE				DIRECT MUMPS
modeling method	Indirect BEM ATV 20-3000 Hz	FEM PML ATV 1 20-500 Hz	FEM PML ATV 2 500-3000Hz	FEM AML ATV 1 20-500 Hz	FEM AML ATV 2 500-3000Hz	FEM AML ATV 2 20-3000Hz
# nodes	4,893	47,155	181,676	12,947	116,120	116,120
# elements	4,894	263,661	1,035,257	66,849	649,857	649,857
# field points	22	22	22	22	22	22
Single RPM Acoustic Response						
# processors	8	8	8	8	8	1,4 threads
time (min)	237	1.3	17	0.3	12	89
RAM at start (Gb)	6.8	3.4	7	1	2.6	2.8
RAM steady state (Gb)	6.8	1.7	3.6	1	2.6	2.8
# freqs	150	25	126	25	126	150
equivalent 1 processor time/freq	12.64	0.42	1.08	0.096	0.76	0.59
ATV computation						
# processors	8	8	8	8	8	1,4 threads
time (min)	**243**	7.5	**333**	4	**222**	**125**
RAM at start (Gb)	6.8	3.4	5.6	1	2.6	2.8
RAM steady state (Gb)	6.8	1.7	2.2	1	2.6	2.8
# freqs	150	25	126	25	126	150
equivalent 1 processor time/freq	**12.96**	2.4	**21.14**	1.28	**14.10**	**0.83**
Full RPM Modal ATV Response 41 RPMs						
time (min)	1	0.2	1	0.2	1	1
delta RAM (Gb)	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
# freqs	12259	2009	10291	2009	10291	12259
time/freq	very small	very small	very small	very small	very small	very small

Machine : Windows 64 bit Dual Quad-Core Desktop (8 cores in total) – 24GB RAM

- **For normal acoustic response (fixed RPM):**
  - At low frequency FEM AML with iterative solver is the fastest solution
  - For a broader frequency range FEM AML with direct MUMPS solver is the preferred solution
  - Solving time per frequency increases with the frequency when using iterative solver

- **For full run-up of 41 RPM's:**
  - *Use of ATV FEM PML/AML computed with direct MUMPS solver is the fastest approach*
  - *Use of ATV FEM PML/AML computed with iterative solver is longer then direct BEM*

- ***FEM AML about 1.5 faster then FEM PML***

Conclusions

- A new methodology has been developed in FEM for radiated problems called **PML/AML**

- On top of it **recent innovations** have also been made:
  - On the iterative FEM solver
  - New direct MUMPS FEM solver implemented

- As shown for an industrial passenger car V6 engine model the new FEM PML and AML approaches provide **excellent results up to 5kHz** and keep outperforming an FMBEM approach up to 10kHz.