Mid-frequency challenge – efficient simulation of sound radiation from electric motors

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19.03.2018, DAGA 2018 Munich
DAGA 2017 revisited: electric drives as a source of noise

Electro Mobility
Marine Propulsion
Power Engineering
Industrial Drives
Vacuum Cleaner, Fan
Universal Motors, …
Concept of FEM-based noise computation: workflow

ANSYS Mechanical with Electric Drive Acoustics inside ANSYS

Electromagnetic Analysis

EM excitation loads

DFT

Excitation Loads

Harmonic Vibration Analysis

Oscillation, ERP, Waterfall Plot

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Concept of FEM-based noise computation: acoustic results

Identify critical OPs

Vibration shapes for critical OPs

Radiated acoustic sound field

ERP [dB]

DAGA 2017: vibration ERP workflow

DAGA 2018: acoustics workflow
Concept of FEM-based structure-borne sound computation

- Equivalent Radiated Power (ERP) as a rough estimate
- mean-square structural normal velocity $v_n$ on radiating surface $A$

- advantage: returns a fast figure of generated noise
  - indicates critical operating points
  - efficient comparison of designs

- performance factors
  - electromagnetic excitation: rpm interpolation for complex load spectra
  - structural vibration: mean square $v$ efficiently computed in modal subspace
  - acoustics: no acoustic field calculation, no meshing of fluid space

$$P_{ERP} = \frac{1}{2} \rho c \sigma \iint_A |v_n|^2 dA$$

ERP: radiation efficiency $\sigma = ?$ → air-borne sound radiation in the following!

Helmholtz number: non-dimensional scale for sound radiation tasks

Helmholtz number

\[ He = k \cdot a = \frac{2\pi a}{\lambda} \]

Rule of thumb

- He < 1: low frequency problem
- He ≥ 10: high frequency problem

Electric motor Helmholtz

- f=100 Hz, \( \lambda = 3.4m \), He=0.4
- f=1 kHz, \( \lambda = 0.34m \), He=4
- f=10 kHz, \( \lambda = 0.034m \), He=40

Hermann von Helmholtz
Mid-frequency challenge for mesh-based acoustics simulation

- $f_{\text{max}}$ controls element size
  \[ \lambda_{\text{min}} = \frac{c}{f_{\text{max}}}, \quad \text{ESIZE} \approx \frac{\lambda_{\text{min}}}{10} \]

- $f_{\text{min}}$ controls acoustic domain size due to absorbing boundary conditions ABC
  \[ \lambda_{\text{max}} = \frac{c}{f_{\text{min}}}, \quad R \approx \frac{\lambda_{\text{max}}}{4} \]

- Wide frequency range $f_{\text{min}} < f < f_{\text{max}}$
  \[ \rightarrow \text{large acoustic domain } R \text{ & small elements } \text{ESIZE} \rightarrow \text{huge number of DOFs} \]
  \[ \rightarrow \text{exponential increase in computational resources} \rightarrow \text{idea: } f \text{ parameterization} \]
Acoustic HPC performance optimization: frequency sub-ranges

- smaller range $f_{\text{min}}$ to $f_{\text{max}}$ for each band
- smaller air domain $R(f)$
- larger elements $\text{ESIZE}(f)$
- smaller number of DOFs
- more efficient solution in each band

Table of parameterized frequency bands

- Full model for total freq. range 3 Mio. DOF's
- freq. band 1 240,000 DOFs
- freq. band 2 300,000 DOFs
- freq. band n 410,000 DOFs
ANSYS HPC Mesh Domain Decomposition (MDD)

• decomposes the problem into “n” subset of elements
• each mesh group is computed by one core

Mesh domain 1
Mesh domain 2
Mesh domain 3
Mesh domain n

Core 1
Core n

• MDD smaller sub-domains
• distributed on all cores
• less RAM is required per core
• solves one frequency at a time
• huge MPI data communication
• decomposes the problem into “n“ frequency bands
• each band is calculated by “NProcPerSol“ cores
  • NSUBST,50 with 100 CPU cores (-dis -np 100) & DDOPTION,FREQ, NProcPerSol =2
  → 50 parallel sets of calculations, each working on a frequency point using 2 cores for MDD
  (2 groups of elements per frequency).

• large amount of RAM is required
• solves one frequency band at a time
• some CPU's may remain idle in FDD
• very little MPI data communication
**Acoustic HPC performance optimization: balancing of MDD & FDD**

<table>
<thead>
<tr>
<th></th>
<th>14 CPU, 180 GB RAM</th>
<th>frequency bands: no</th>
<th>frequency bands: no</th>
<th>frequency bands: yes</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0...5 kHz, 500...2500 rpm</td>
<td>MDD: no</td>
<td>FDD: no</td>
<td>MDD: yes</td>
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<tr>
<td># DOFs</td>
<td>3 Mio.</td>
<td>3 Mio.</td>
<td>0.6 Mio</td>
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<td>used CPU</td>
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<td>Elapsed time [hours]</td>
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<tr>
<td>RAM [GB]</td>
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<td>110</td>
<td>32</td>
<td></td>
</tr>
</tbody>
</table>

**Elapsed time [h]**

**Amount of Memory Required to Solve the Model**

![Graph showing computational time and memory requirements](image)
Acoustic HPC performance optimization: high-frequency

- low 10 Hz to high-frequency 10 kHz: 30 steps
- from 500rpm to 5000rpm: 10 load cases

- elapsed time 7 hours for 300 solutions on a machine with 14 CPU’s and 180 GB RAM
SPL at 1 kHz

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Structure-borne (ERP) vs. air-borne sound power level: 500 rpm
Structure-borne (ERP) vs. air-borne sound power level: 5000 rpm

Sound Power Level Str-borne Vs Air-borne @ n = 5000 rpm

- Str-borne Model
- Air-borne Model

Sound Power Level [dB re: 1e-12 W]

Frequency [Hz]

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Air-borne sound analysis: resulting radiation efficiency $\sigma \neq 1$

\[ L_\sigma = 10 \log \frac{\sigma}{\sigma_0} \text{[dB]}, \quad \sigma_0 = 1 \]

- complicated behavior
- no good experience with look-up tables for $\sigma$
Waterfall Diagram: 0 - 10kHz and n [500 - 5000 rpm]

Mode shape 1 (607 Hz) at resonance

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Conclusions and outlook for electric drive acoustics

• electromagnetic – structural vibration – acoustics workflow
• from structure-borne (ERP) to air-borne sound radiation
• ANSYS efficiently computes multi-rpm air-borne sound up to 10 kHz
• SPL waterfall diagram from 500 rpm to 5000 rpm and from 10Hz to 10kHz within 7 hours elapsed time on a computer with 14 cores and 180 GB RAM
• ANSYS Mechanical HPC performance optimization based on
  • optimal selection of absorbing boundary condition
  • parameterized frequency f, element size E\text{SIZE}(f), acoustic domain size R(f)
  • optimized balancing of MDD & FDD adapted to model size, freq. range & hardware

• outlook to DAGA 2019 😊
acoustic model order reduction for further speed-up