# A model-based approach for the evaluation of noise emissions in external gear pumps

Sangbeom Woo

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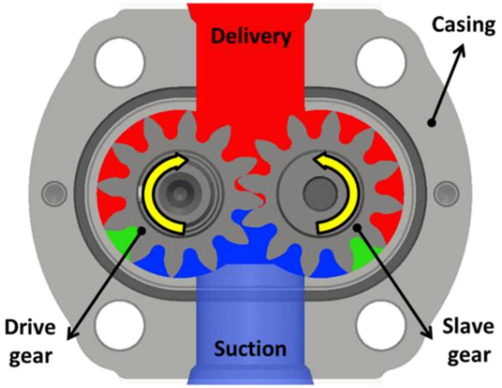
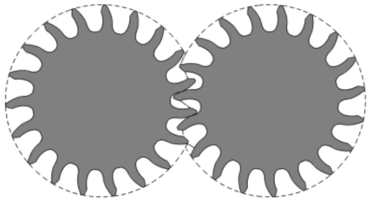
# Introduction



- Noise is a key issue for current hydraulic systems and limiting factor to the spread of hydraulics into new fields
- Displacement machines are the primary sources of noise in fluid power systems
- Reference: **External Gear Pumps**




- Successful design solutions involving gears focusing on **flow oscillations:**
  - Negrini (1996) – Dual-flank gears
  - Fiebig (2010) –Compression filter volumes
  - Mucchi (2010) – Split gear solution
  - Lätzel (2012) – Cycloidal gear profiles
  - Morselli (2015) – Helical asymmetric gears

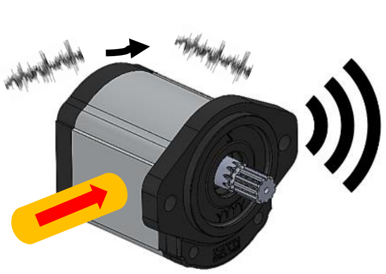

Asymmetric gears


Helical gears

# Introduction



- All sources of noise and how noise propagates through the system are not well understood
- Noise generation in external gear pumps involves **three domains**



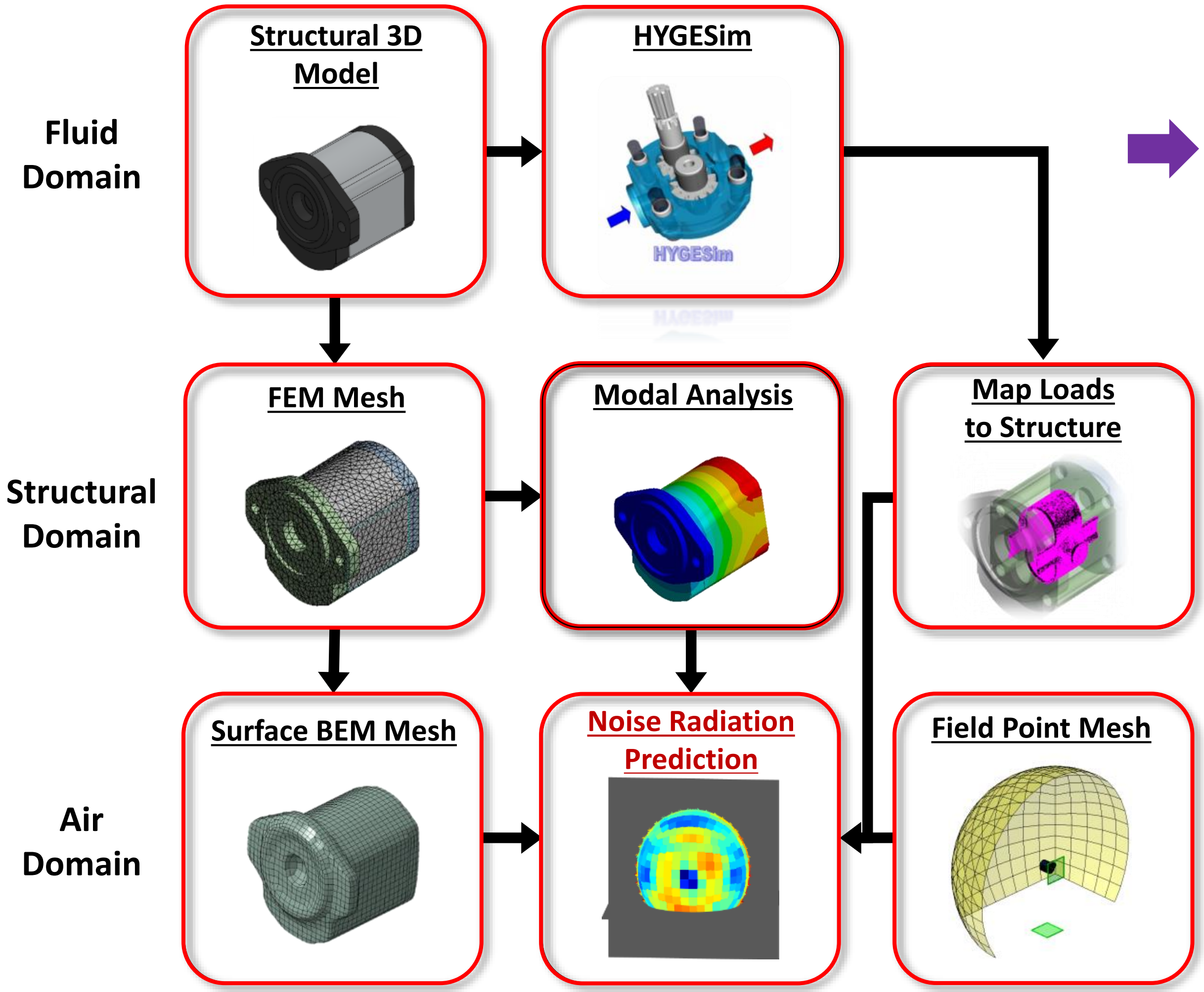
| Fluid-Borne Noise (FBN) | Structure-Borne Noise (SBN) | Air-Borne Noise (ABN) |
|---|---|---|
| Pressure fluctuations in the fluid | Forces applied to the structure cause vibrations | Vibrations transmitted through the air from the structure to the field |

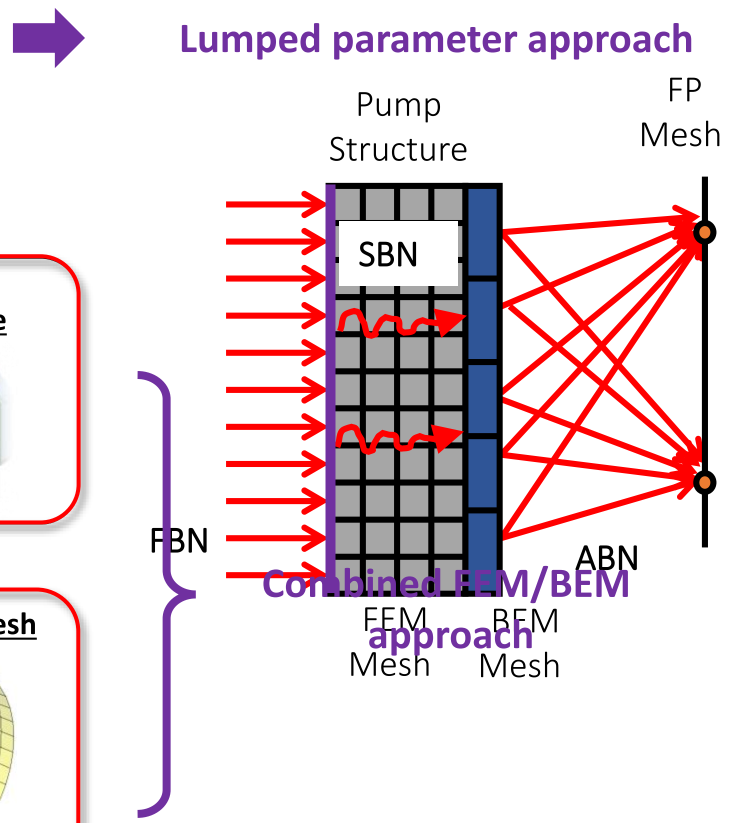
Aims of the research:

- Develop the noise prediction model which ***considers all possible noise sources*** and ***interaction between three domains***
- Identify the effect of the pump mounting conditions on the emitted noise in the numerical modeling works

# Simulation Model Structure

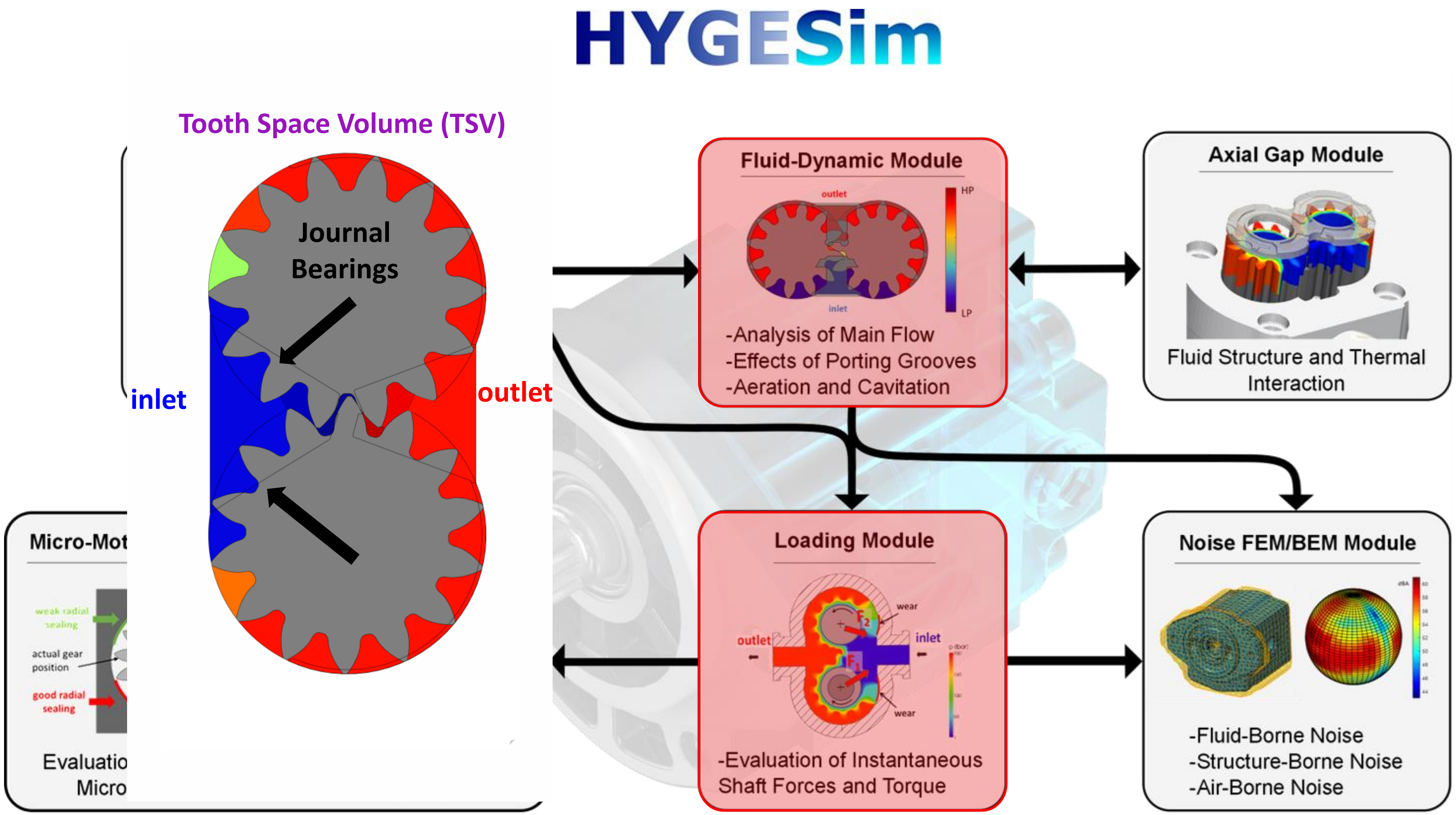




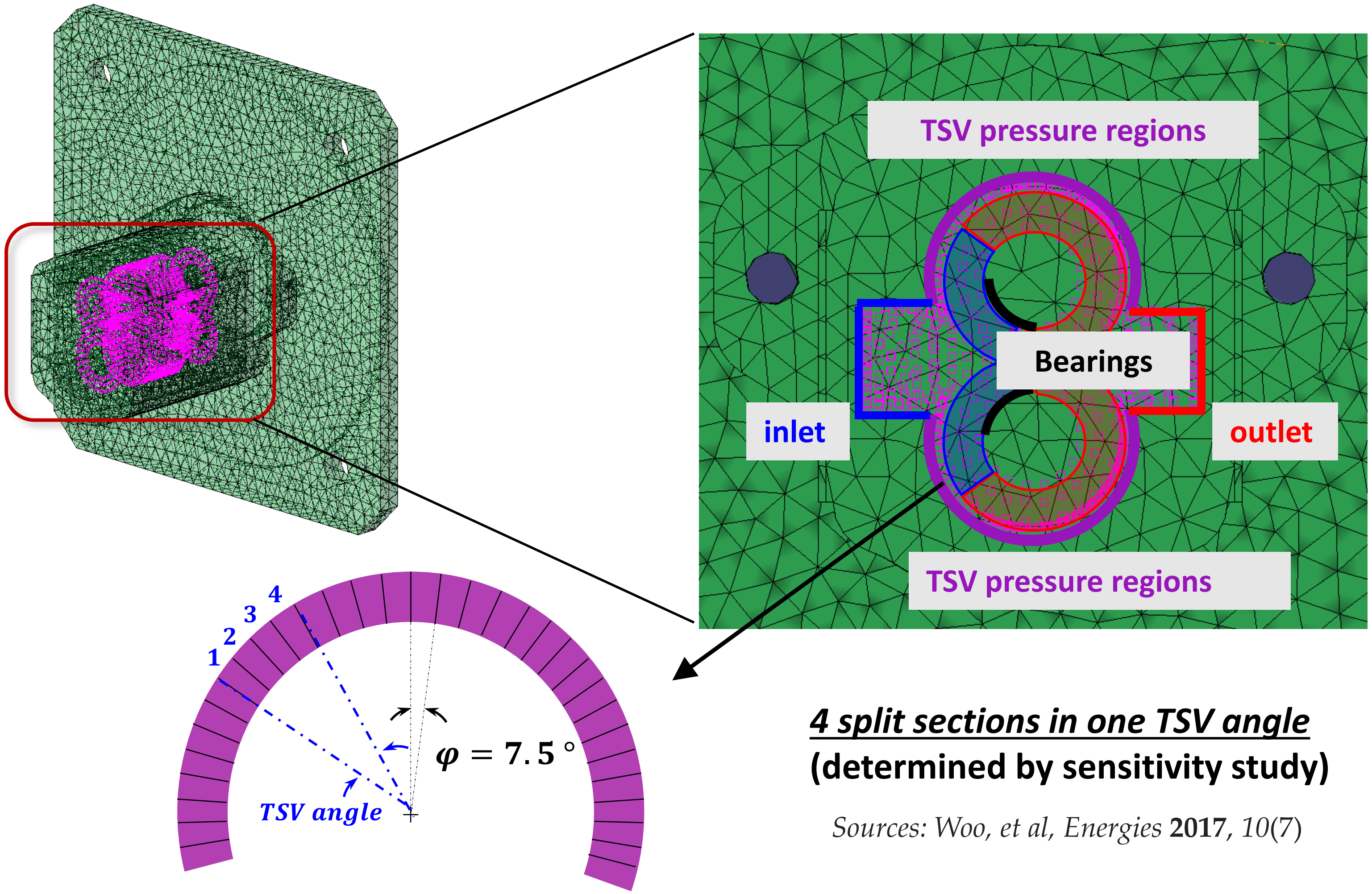



# Modeling FBN – HYGESim





# Mapping Loads to Structures




***4 split sections in one TSV angle***
**(determined by sensitivity study)**

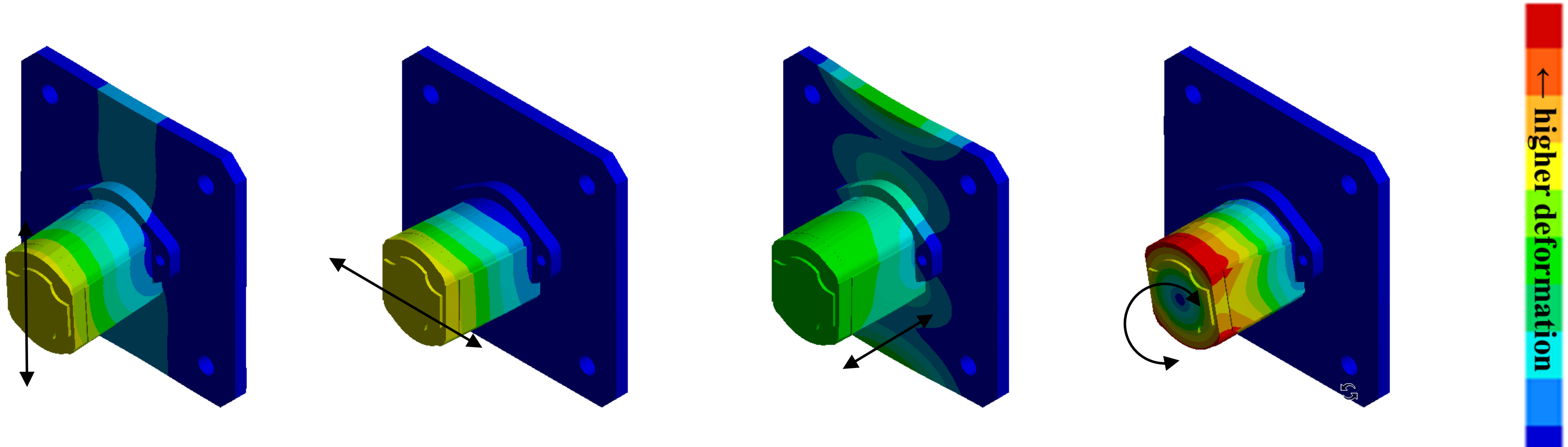
*Sources: Woo, et al, Energies* **2017**, *10*(7)

# Structural Analysis (Finite Element Method)

Maha Fluid Power RESEARCH CENTER PURDUE UNIVERSITY

- Numerical Modal Analysis
  - Modes in the audible frequency (20 Hz ~ 20 kHz) are considered

$\Phi_k$:




< Bending Modes > <Longitudinal mode > <Torsional Mode >

- **<u>Modal superposition technique</u>** is used to determine the structural forced response

$$\{w\} = \sum_{k=1}^{M} q_k \Phi_k = [\Phi] \cdot \{q\}$$

$w$ : Displacement (Forced response of structure)

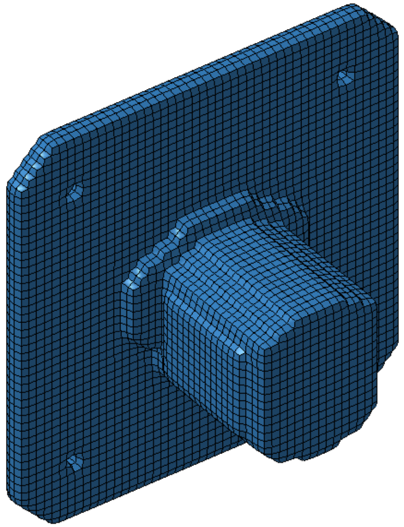
$q_k$: Modal participation factors

$\Phi_k$: Modal vectors (mode shapes)

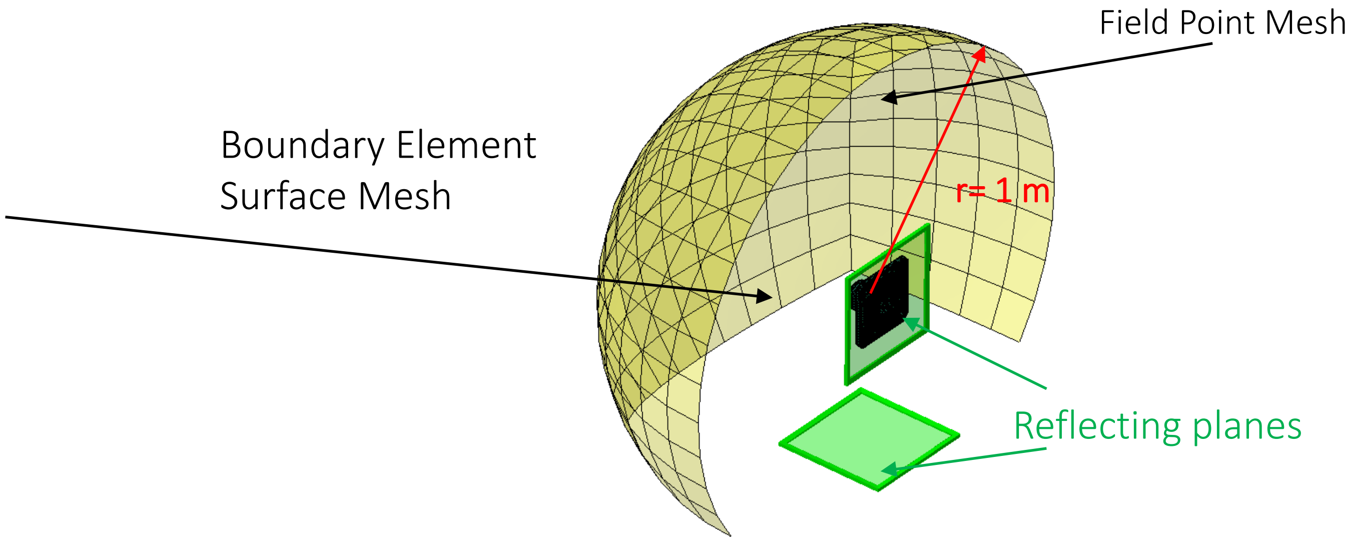
# Acoustic Analysis (Boundary Element Method)



- Boundary Element Surface Mesh



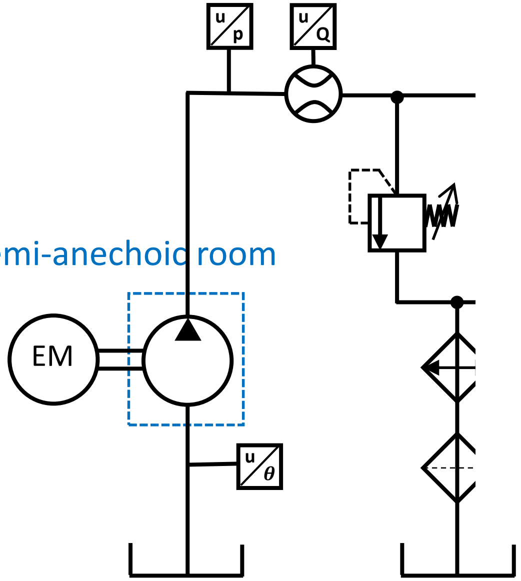
- Field Point Mesh & Acoustic Environments



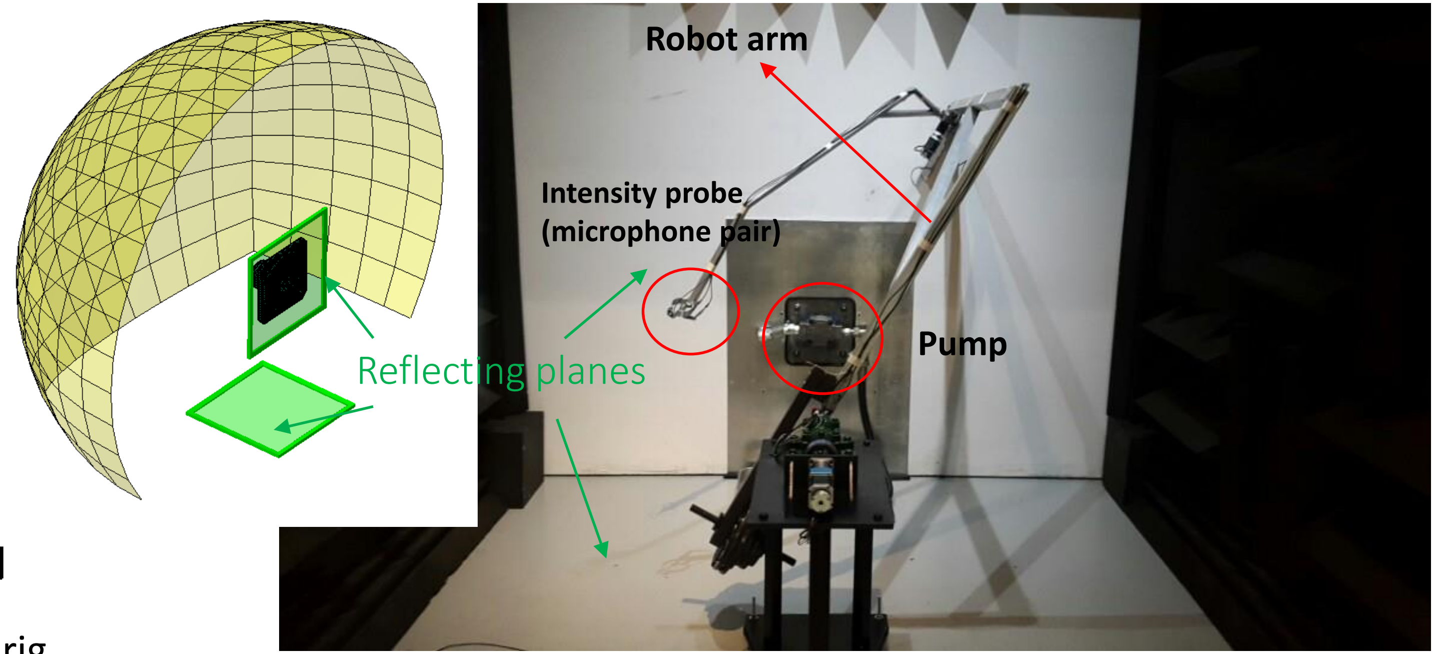

- Generated on the exterior surface of FEM Mesh
- Uniformly distributed coarsened mesh for efficient calculation

- Visualization mesh in acoustic domain
- Can be regarded as microphone arrays
- Mimic the acoustic environments of semi-anechoic chamber

# Noise Measurement




<Anechoic chamber test rig hydraulic schematic>



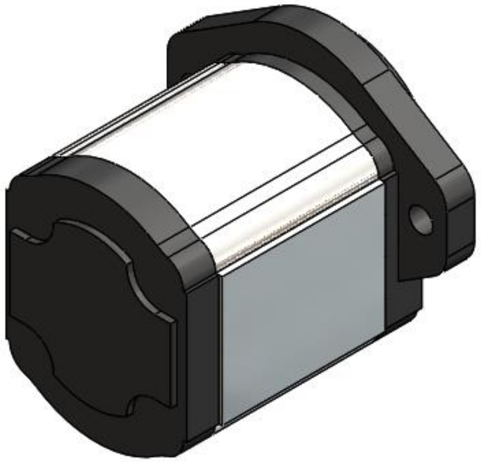

ISO 9614-1 (Acoustics—Determination of Sound Power Levels of Noise Sources using Sound Intensity. Part 1: Measurement at Discrete Points)

- The inlet temperature was kept constant (Steady-state conditions)
- Sound intensity was measured at discrete points using the robot arm

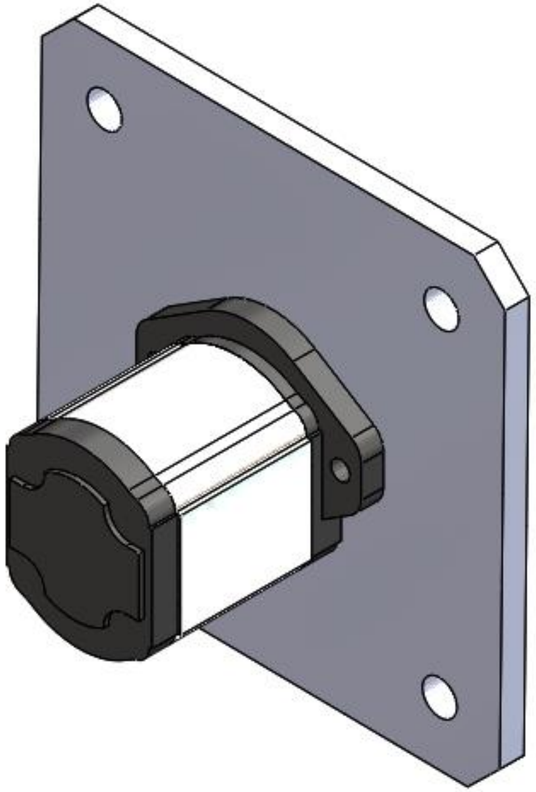
# Mounting Conditions in Numerical Model



- Standalone Pump



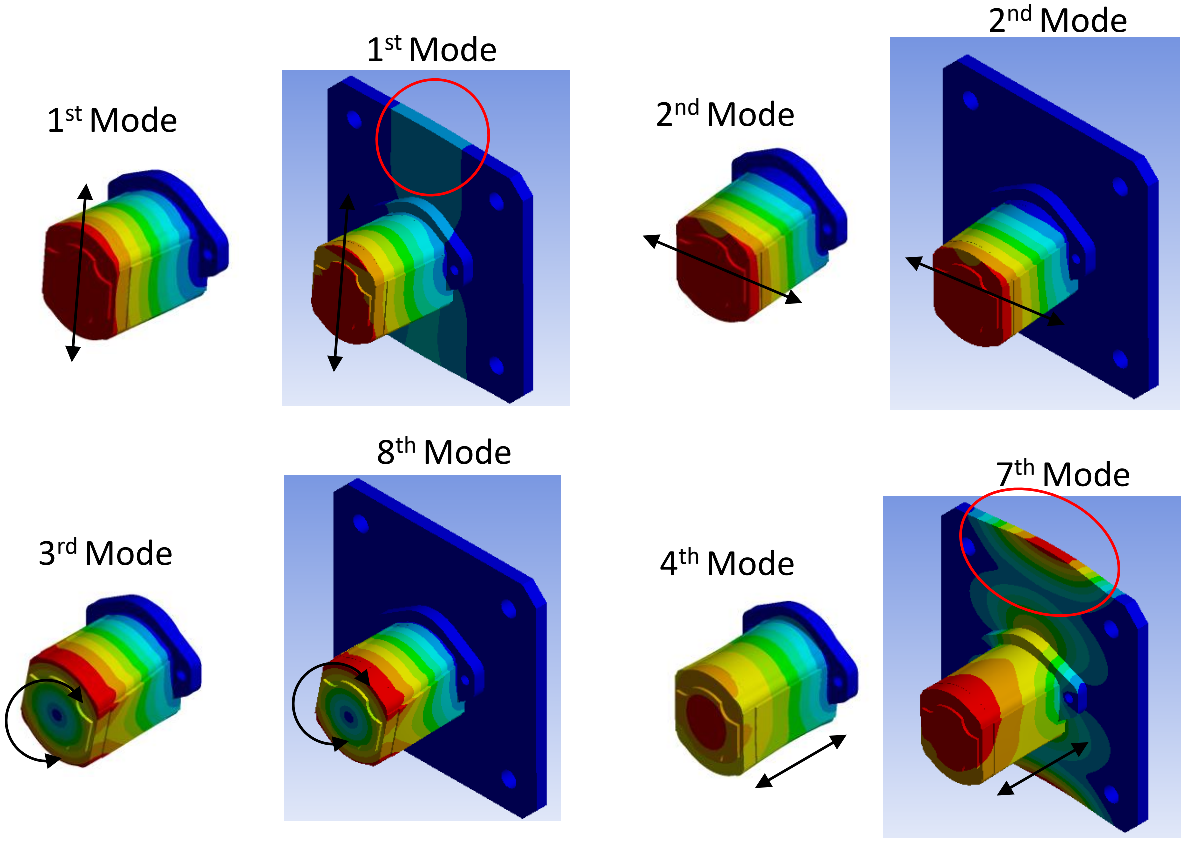
- Pump with structure



# Modal Analysis Results

| Mode | Standalone | with structure |
|---|---|---|
| | Normalized Frequency | |
| 1 | 1.00 | 0.58 |
| 2 | 1.02 | 0.91 |
| 3 | 1.95 | 1.00 |
| 4 | 2.75 | 1.07 |
| 5 | 3.71 | 1.34 |
| 6 | 3.89 | 1.37 |
| 7 | 5.18 | 1.74 |
| 8 | 5.43 | 1.93 |
| 9 | 5.60 | 2.27 |
| 10 | 5.72 | 2.30 |
| 11 | 5.85 | 2.34 |
| 12 | 6.27 | 2.37 |
| 13 | 6.36 | 2.60 |
| 14 | 6.60 | 0.72 |
| 15 | 6.94 | 3.02 |
| 16 | 7.04 | 3.16 |
| 17 | | 3.34 |
| 18 | | 3.47 |
| 19 | | 3.47 |
| 20 | | 3.67 |

***(Reference of normalization:***
***1st numerical modal frequency of standalone pump***

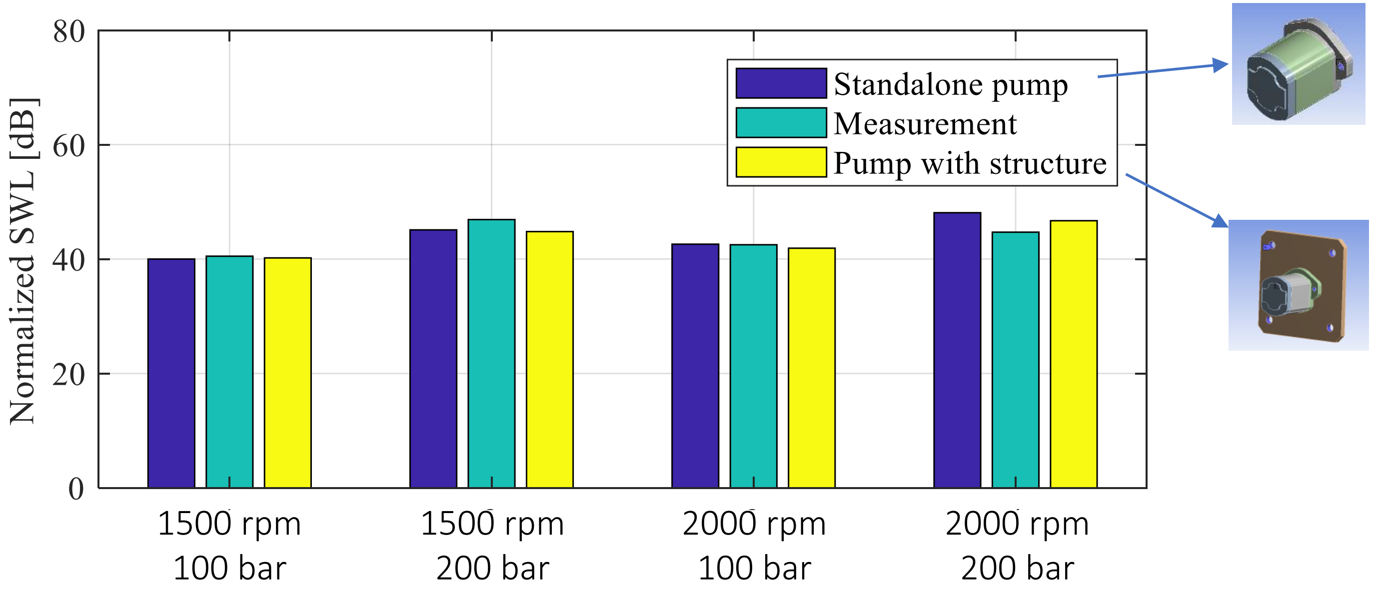



- Including structures lower the first resonant frequency
- Some mode shapes contain the axial motion of the plate

# Normalized overall SWLs



*(Reference of normalization:*
*Sound power of the experimental noise floor)*

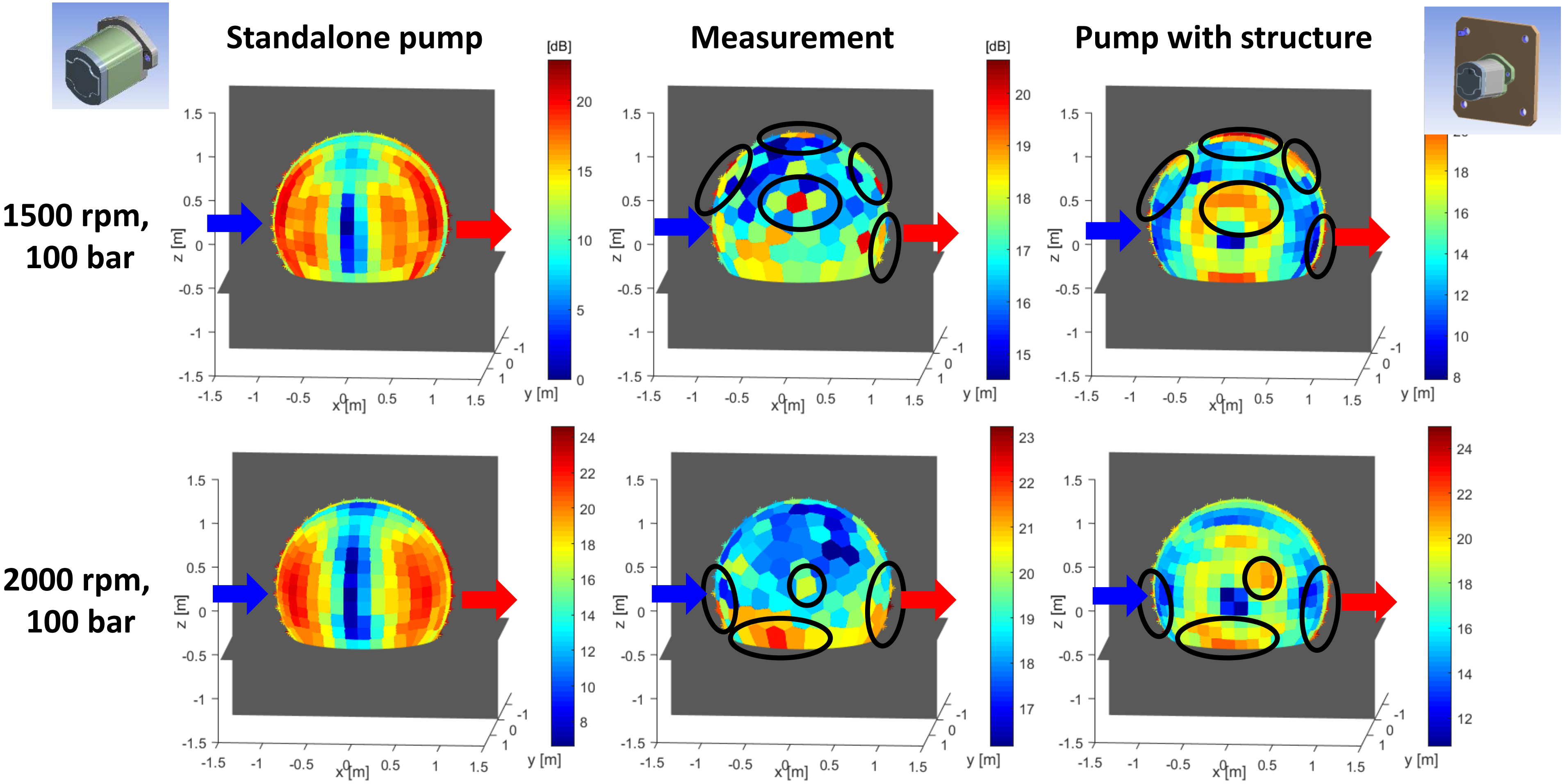



| Operating conditions | Standalone pump | Measurement | Pump with structure |
|---|---|---|---|
| 1500 rpm, 100 bar | 40.0 dB (-0.5 dB) | 40.5 dB | 40.2 dB (-0.3 dB) |
| 1500 rpm, 200 bar | 45.1 dB (-1.8 dB) | 46.9 dB | 44.8 dB (-2.1 dB) |
| 2000 rpm, 100 bar | 42.6 dB (+0.1 dB) | 42.5 dB | 41.9 dB (-0.6 dB) |
| 2000 rpm, 200 bar | 48.1 dB (+3.4 dB) | 44.7 dB | 46.7 dB (+2.0 dB) |

- the range of discrepancy becomes smaller ( [-1.8~3.4 dB] → [-2.1~2.0 dB] )

# Normalized SPLs (Delivery pressure: 100 bar)

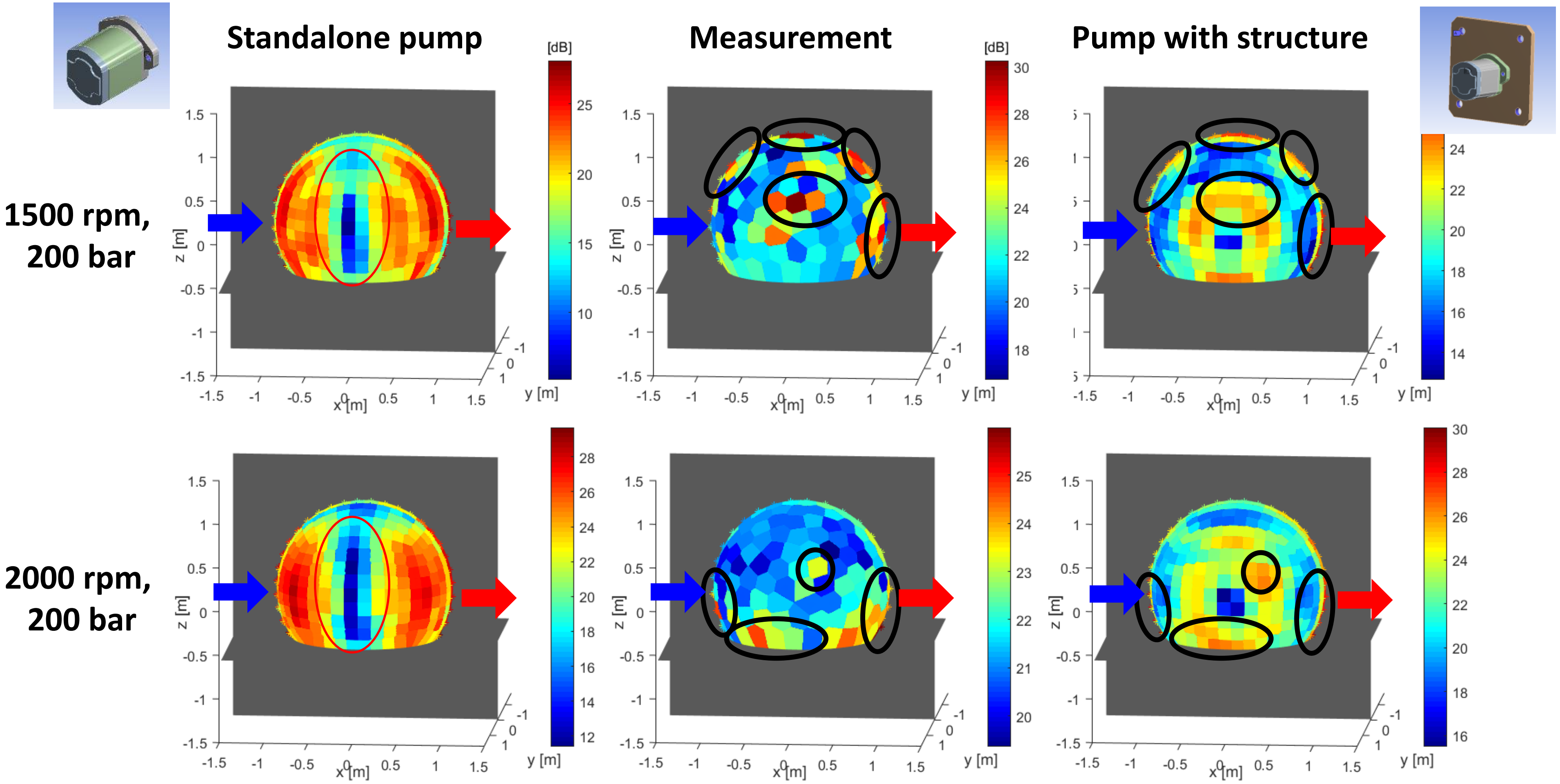





- By including structures, the acoustic model starts to capture the noisy areas

# Normalized SPLs (Delivery pressure: 200 bar)





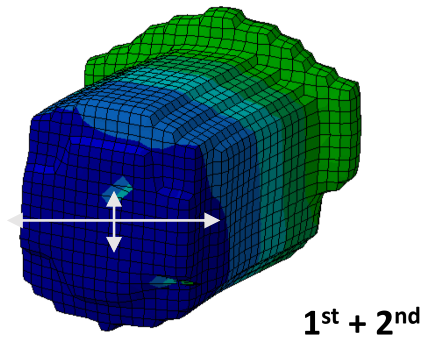

- Noisy areas remain almost the same at the same shaft speed

# Vibration of ‘standalone pump’

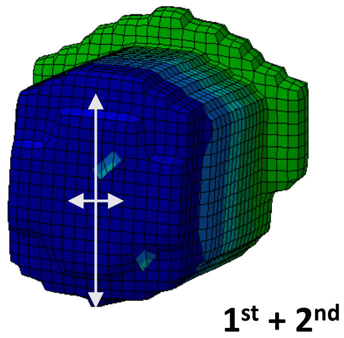


- Forced response of the structure (Displacement)

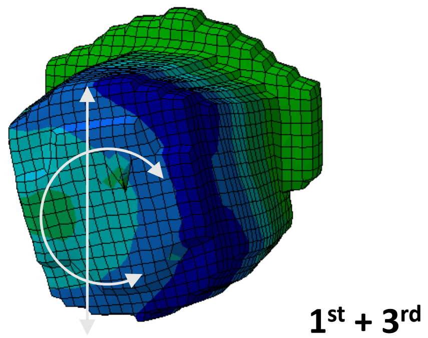
**600 Hz (2nd harmonic)**




**2700 Hz (9th harmonic)**

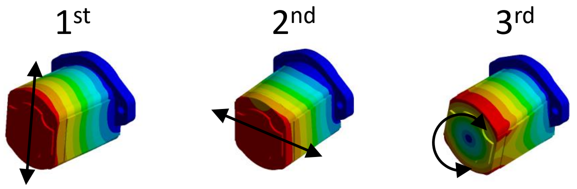



**4500 Hz (15th harmonic)**





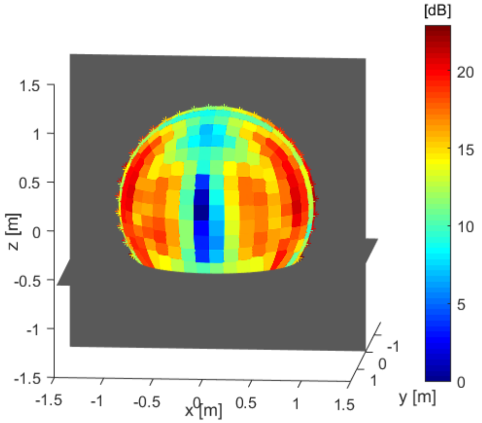
- All the motions appear to be the superposition of 1,2, and 3 mode shapes




- No axial motions are observed at all frequencies up to 5 kHz
- Low noise emission in axial direction

↓

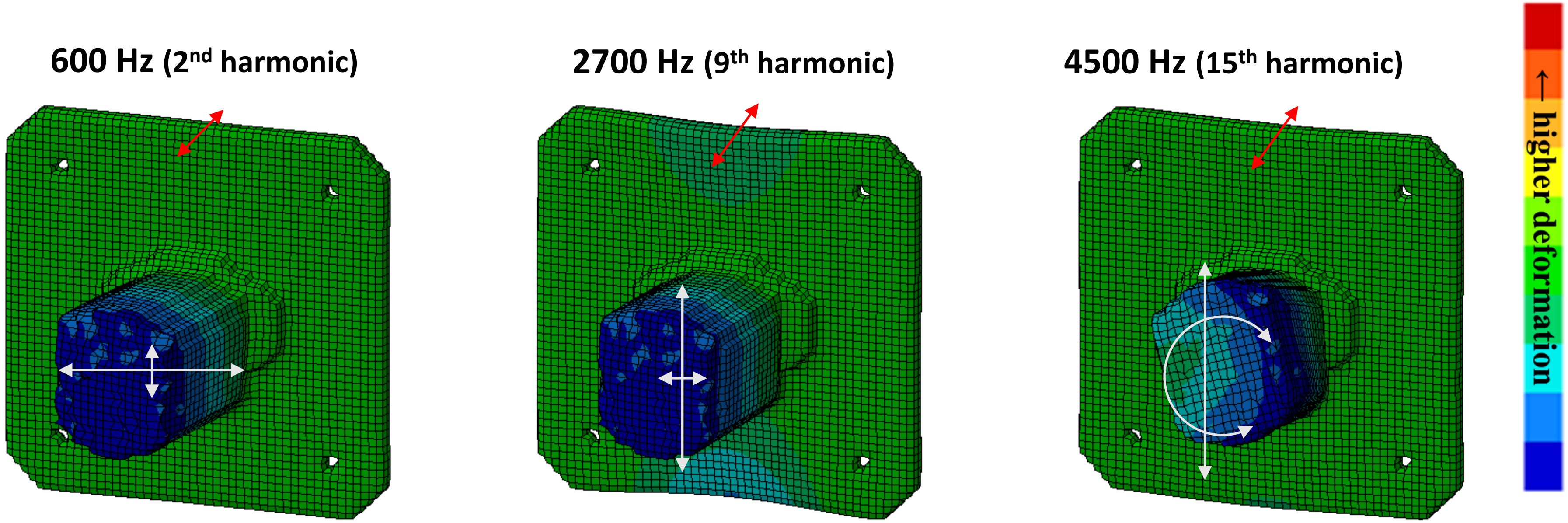
Limitations of the standalone pump model



# Vibration of 'pump with structures'



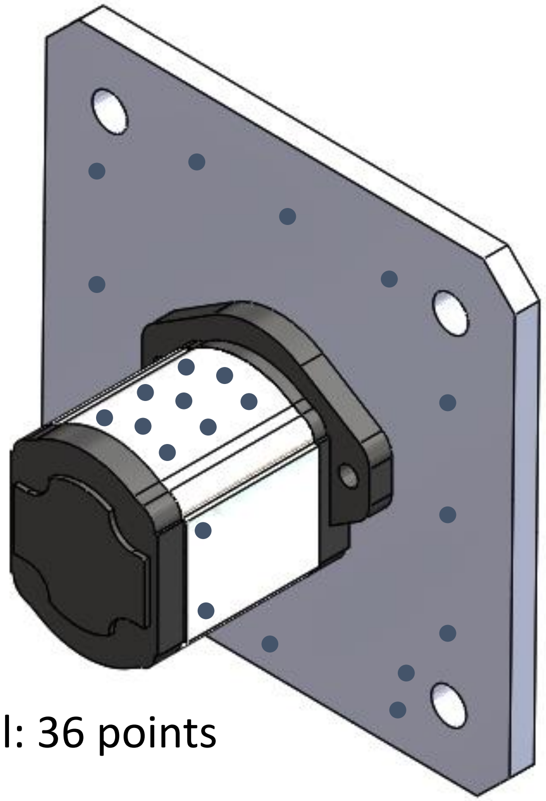
600 Hz (2nd harmonic) 2700 Hz (9th harmonic) 4500 Hz (15th harmonic)




- Vibrations of the pump are similar to those of the standalone pump
- Vibrations of plate in axial direction also can be observed
- It can contribute to noise emissions in axial directions

# Vibration Measurement





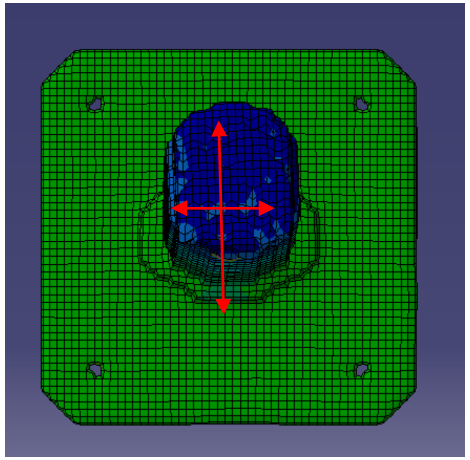
Total: 36 points

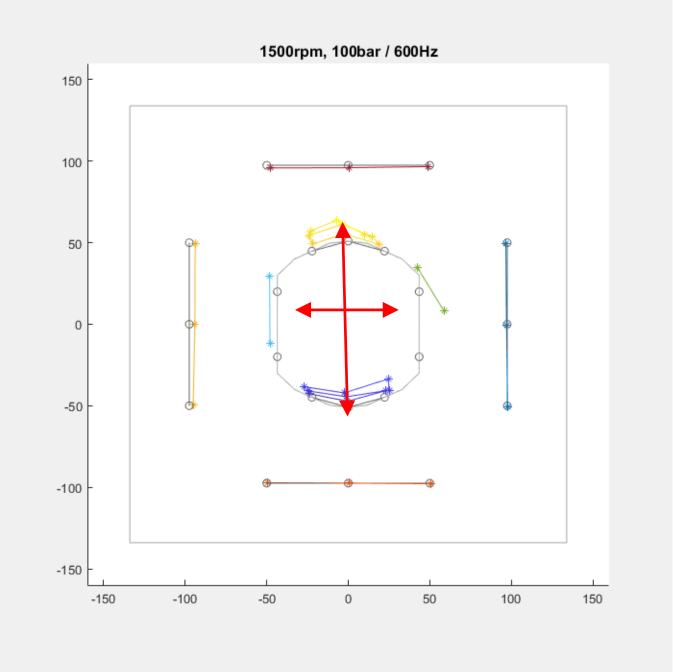
- Accelerometers were mounted to pump and plate during the pump operation
- Acceleration signals were synchronized using cross-correlation

# Vibration Comparisons

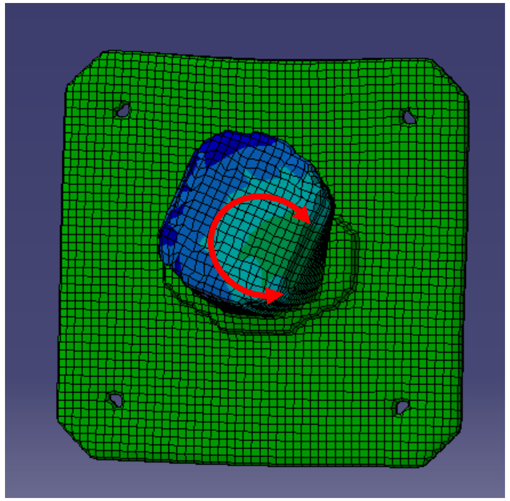


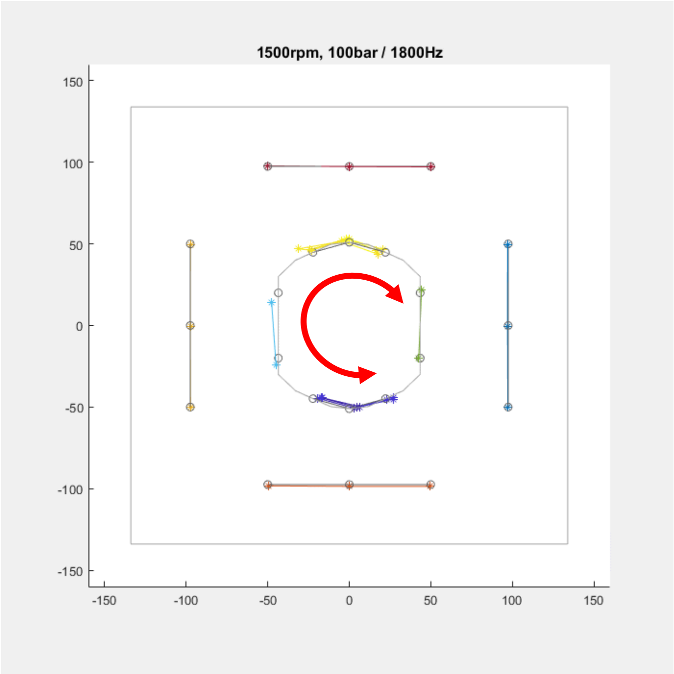
**< Bending Motion >**






**< Torsional Motion >**






- Vibration prediction using modal superposition technique is valid
- Vibration of the plate can be observed in the measurement

# Model Potentials

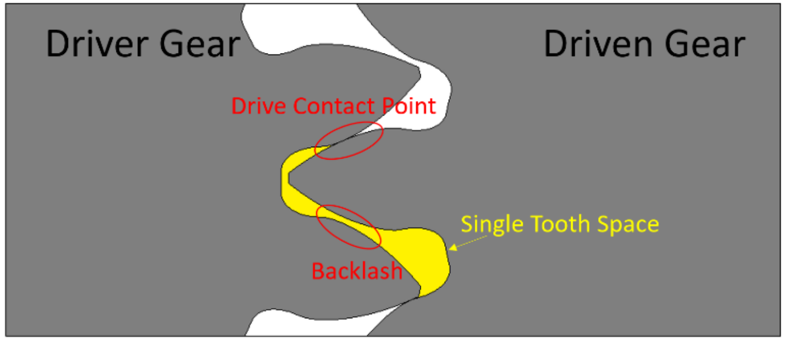


- Considered two different gears designed to *fit into the same housing*

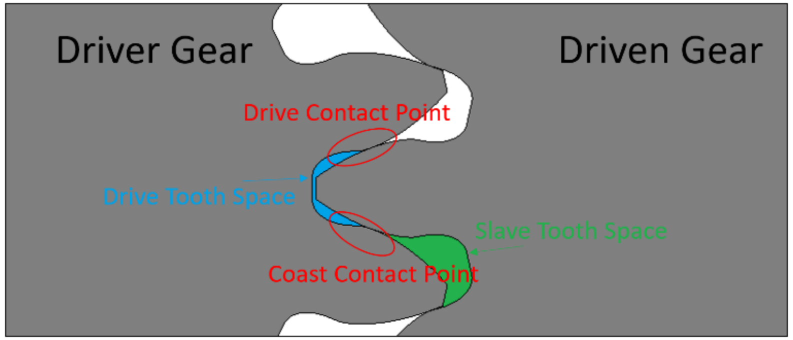
*Sources: Woo, et al, BATH/ASME FPMC* **2017**

- Displacement: 24 cc/rev
- Number of teeth: 14
- Pressure angle: 20 °
- Center distance: 35 mm

Single-flank gear




Dual-flank gear

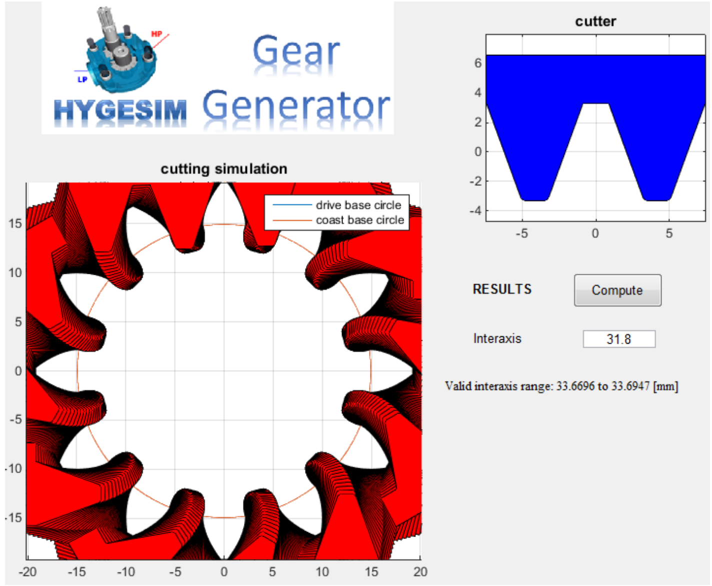


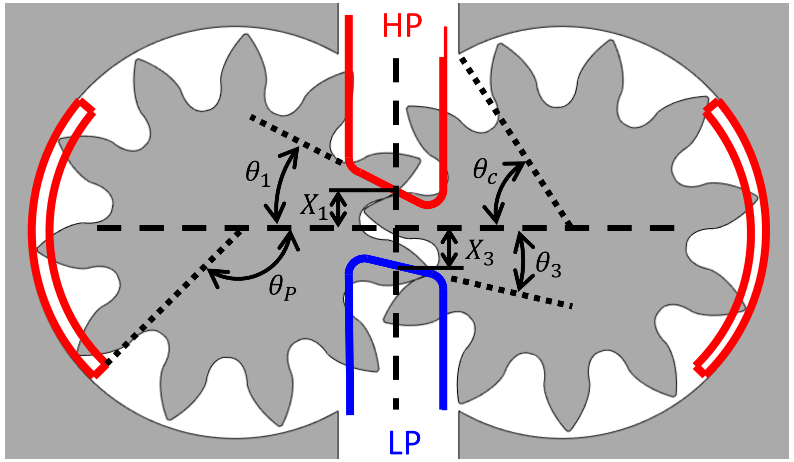

| Overall SWL [dB] | Dual-flank | | Single- flank | Difference |
|---|---|---|---|---|
| 1000 rpm, 50 bar | 71.9 dB | < | 74.3 dB | 2.4 dB |
| 1000 rpm, 100 bar | 73.5 dB | < | 75.4 dB | 1.9 dB |

**Acoustic model confirmed lower noise level of the dual-flank design**

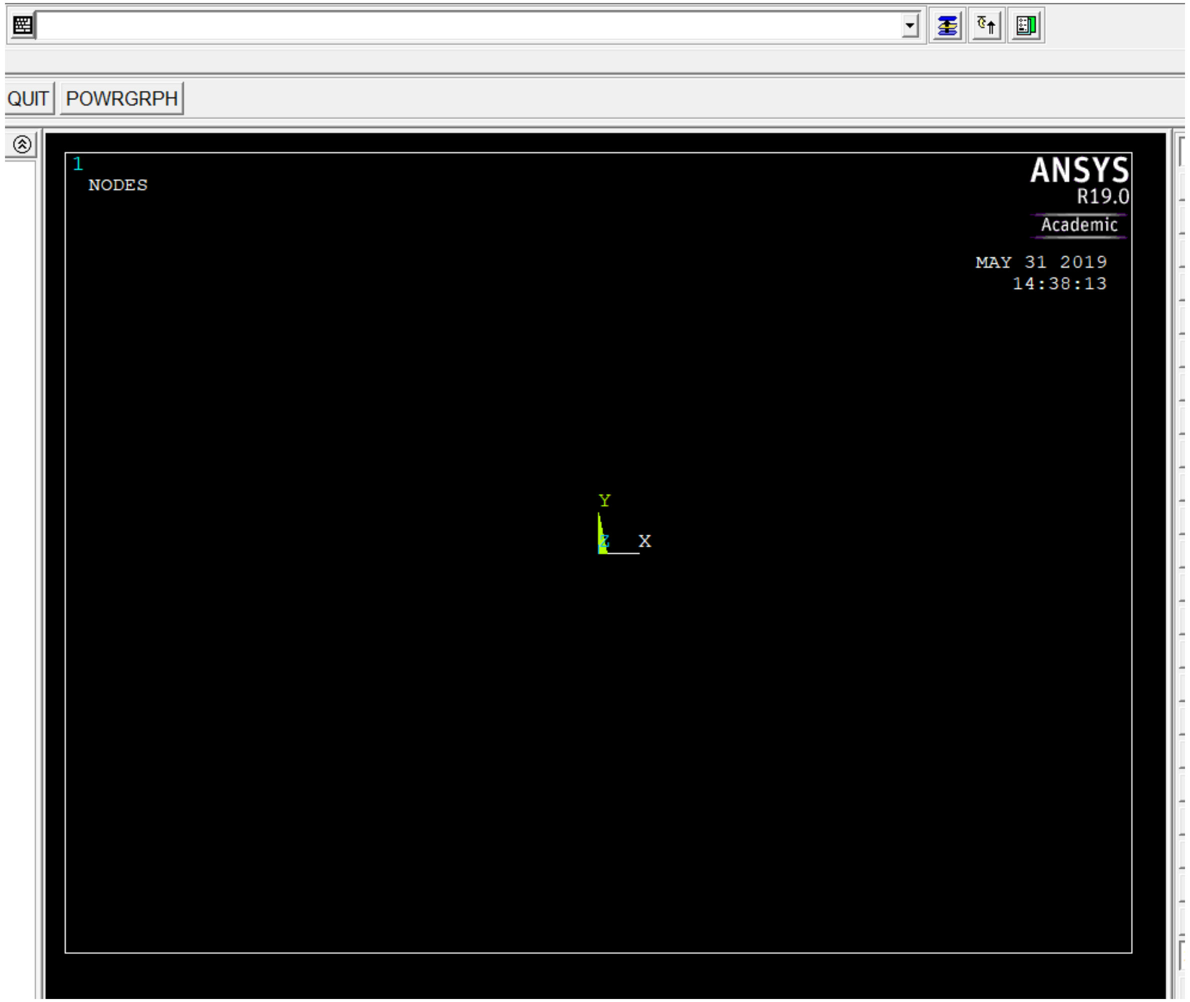
# Model Potentials

- Gear & Groove Design Parameters




- Parameterization of acoustic model for optimization




- **Objective function: Sound Power**

# Thank you. Questions?