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

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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
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**

<table>
<thead>
<tr>
<th>Fluid-Borne Noise (FBN)</th>
<th>Structure-Borne Noise (SBN)</th>
<th>Air-Borne Noise (ABN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure fluctuations in the fluid</td>
<td>Forces applied to the structure cause vibrations</td>
<td>Vibrations transmitted through the air from the structure to the field</td>
</tr>
</tbody>
</table>

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

- Structural 3D Model
- HYGESim
- Modal Analysis
- Map Loads to Structure
- Field Point Mesh
- Noise Radiation Prediction
- Surface BEM Mesh
- FEM Mesh
- Fluid Domain
- Structural Domain
- Air Domain

Lumped parameter approach

Combined FEM/BEM approach

FP Mesh

SBN

FBN

ABN
Modeling FBN – HYGESim

HYGESim

Tooth Space Volume (TSV)

Journal Bearings

Fluid-Dynamic Module
- Analysis of Main Flow
- Effects of Porting Grooves
- Aeration and Cavitation

Axial Gap Module
 Fluid Structure and Thermal Interaction

Loading Module
- Evaluation of Instantaneous Shaft Forces and Torque

Noise FEM/BEM Module
- Fluid-Borne Noise
- Structure-Borne Noise
- Air-Borne Noise
Mapping Loads to Structures

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

Sources: Woo, et al, Energies 2017, 10(7)
• **Numerical Modal Analysis**
  – Modes in the audible frequency (20 Hz ~ 20 kHz) are considered

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

- \(w\): Displacement (Forced response of structure)
- \(q_k\): Modal participation factors
- \(\Phi_k\): Modal vectors (mode shapes)

• **Modal superposition technique** is used to determine the structural forced response
Acoustic Analysis (Boundary Element Method)

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

- **Field Point Mesh & Acoustic Environments**
  - Visualization mesh in acoustic domain
  - Can be regarded as microphone arrays
  - Mimic the acoustic environments of semi-anechoic chamber

- 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

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

(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

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

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

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

- 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

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

- Vibration prediction using modal superposition technique is valid
- Vibration of the plate can be observed in the measurement
• Considered two different gears designed to *fit into the same housing*

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

![Diagram of single-flank gear](image1)

![Diagram of dual-flank gear](image2)

<table>
<thead>
<tr>
<th>Overall SWL [dB]</th>
<th>Dual-flank</th>
<th>Single-flank</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 rpm, 50 bar</td>
<td>71.9 dB</td>
<td>&lt; 74.3 dB</td>
<td>2.4 dB</td>
</tr>
<tr>
<td>1000 rpm, 100 bar</td>
<td>73.5 dB</td>
<td>&lt; 75.4 dB</td>
<td>1.9 dB</td>
</tr>
</tbody>
</table>

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

Sources: Woo, et al, BATH/ASME FPMC 2017
Model Potentials

- Gear & Groove Design Parameters

- Parameterization of acoustic model for optimization

- Objective function: Sound Power
Thank you. Questions?