Investigation of Noise Transmission through Pump Casing

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Structural Acoustic Paradigm

Pressure loading of surfaces

Pump Structure

Mechanical Response

Sound Radiation

Acoustical Response

Mechanical Coupling

Generation

Transmission

Propagation

Radiation

Perception

5Max1 SPL with Signs
## Analysis Overview

- **Pressure loading of surfaces**
  - Pump
  - Structure
- **Mechanical Response**
- **Sound Radiation**
- **Acoustical Response**

### Generation
- Port pressures
- Bore Pressure
- Pressure Spectrums
- Pressure Module sims

### Transmission
- Empirical Transfer Functions
- Near-field holography

### Propagation
- Surface normal velocity field
- Structural attenuation
- Operational modal analysis

### Radiation
- Acoustic camera
- Far-Field Spherical Harmonics

### Perception
- Sound pressure Intensity
- Sound Power
- ISO Loudness
- FFT
- 1/3 Octave
Characterize the measured sound field in spatial, temporal, and frequency domains.
Automated Spatial Sampling

Custom robot for automated method of measuring sound intensity at any given number of evenly spaced locations.
Floor Reflections Removal

Pump

Direct path
Wall reflected path
Floor reflected path
Microphone

16ST2
Final Grid and Path

225-point Grid

Path:
- Time-based optimization
- 37 min. to run through a whole grid (23 min. faster (54%))

Hemispherical Grid:
- 225 points (26 more points)
- One reflection surface - fulfills ISO 4412
Updated Chamber
Perception
Example Perception Results

Example Sound Intensity Map
SWL: 86.1 dB

Example Loudness Level
mean: 95.2 dB

Example SPL Level [dBc]
mean: 83.1 dB

Example Intensity FFT
Example measurement:
A pump with 9 pistons @ 3000 rpm

Pump Harmonic Frequencies:
450 Hz, 900 Hz, 1350 Hz, 1800 Hz ...

5Max1 SIL Harm 1 (mean: 74.5 dB)

5Max1 SIL Harm 2 (mean: 71.8 dB)
Frequency Analysis

Simplify the frequency analysis

Octave: upper band frequency is the lower band frequency multiplied by $2$

$1/3$ Octave: upper band frequency is the lower band frequency multiplied by $\frac{3\sqrt{2}}{2}$
Spherical Harmonics (radiation)
Measured Pressure Field
(1200rpm, Frequency: 0-25kHz)
Acoustic Holography

Reconstruct the sound field; for every location and any time

1. Particle velocity
2. Sound pressure

Consequentially:
1. Modal vibrational pattern
2. Vector intensity field
3. Far-field radiation pattern
4. Total radiated power

(DeVries, 1994)
Acoustical Meaning of S.H. Functions

- $n = 0$, monopole
- $n = 1$, dipole
- $n = 2$, quadrupole

Pulsating sphere
Pulsating force
Pulsating moment
Wave Equation Decomposition

\[ \nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \]

\[ p(r, \theta, \phi, t) = R(r)P(\theta)\Phi(\varphi) e^{-j\omega t} \]

Radial Part Solution:

\[ R(r) = h_n(kr) \cong \frac{1}{r^n} \]

Directional Part Solution:

\[ P(\theta)\Phi(\varphi) = Y_n^m \]

\[ p = \sum_{n=0}^{+\infty} h_n(kr) \cdot \sum_{m=-n}^{n} a_{nm} \cdot Y_n^m \cdot e^{-j\omega t} \]
From Theory to Practice

Governing equation: \( \nabla^2 p + k^2 p = 0 \) \hspace{1cm} (3)

Boundary condition:

\[
\begin{bmatrix}
\theta_1 & \phi_1 & r_1 \\
\theta_2 & \phi_2 & r_2 \\
\vdots & \vdots & \vdots \\
\theta_M & \phi_M & r_M
\end{bmatrix}, \quad p = \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_M \end{bmatrix}
\]

Possible solution to (3) is:

\[
p = \sum_{n=0}^{+\infty} h_n(kr) \sum_{m=-n}^{n} a_{nm} \cdot Y^m_n
\]
Least Square Fitting

Truncate to finite order \( N \), and write as matrix form:

\[
Y = \begin{bmatrix}
Y_0^0(\theta_1, \phi_1) & Y_1^{-1}(\theta_1, \phi_1) & \ldots & Y_N^N(\theta_1, \phi_1) \\
Y_0^0(\theta_2, \phi_2) & Y_1^{-1}(\theta_2, \phi_2) & \ldots & Y_N^N(\theta_2, \phi_2) \\
\vdots & \vdots & \ddots & \vdots \\
Y_0^0(\theta_M, \phi_M) & Y_1^{-1}(\theta_M, \phi_M) & \ldots & Y_N^N(\theta_M, \phi_M)
\end{bmatrix}
\]

\((N + 1)^2\) unknowns

\[\begin{bmatrix}
c_1 \\
c_2 \\
\vdots \\
c_{(N+1)^2}
\end{bmatrix}, \quad \begin{bmatrix}
q_1 \\
q_2 \\
\vdots \\
q_M
\end{bmatrix}\]

\[Yc = p\]

\[c = Y^{-1}p \iff Yc - p = 0\]

\[c = Y^+p \iff \min(\|Yc - p\|)\]
Measurement Fitting

Measured Complex Pressure - 180 Hz

LS Fitting on N = 0

Fitting Errors on N = 0
Measured Pressure Field
1200rpm, 1\textsuperscript{st} harmonic (180 Hz)
Measured Pressure Field
1200rpm, 1\textsuperscript{st} harmonic (180 Hz)
Measured Pressure Field
2400rpm, 2\textsuperscript{nd} harmonic (720 Hz)
Measured Pressure Field
2400rpm, 2\textsuperscript{nd} harmonic (720 Hz)
Near-Field Holography

In Progress

Far-field holography captures only the propagating pressure waves.

The pressure field also includes **Evanescent waves**, which decay exponentially with distance.

Near-field holography captures both the propagating and evanescent waves.
Near-Field Arm
In Progress

A near field arm is being manufactured.

An additional arm added to the robot will help improvements measurements:

- Easier / faster
- Repeatable
Propagation
Surface Vibrations Example

1200rpm

Position Video

1000 Times slower

Movements exaggerated
Structural Attenuation
In Progress

Consistent spikes in multiple accelerometers yield the structural modes and resonances.

Relative phase of different pump locations reveals the mode shapes.

A designer can
1. Design valve plates based on the Structural Attenuation
2. Add mass/stiffness to effect the Structural Attenuation
Operational Modal Analysis

• Basic Frequency Response Equation (SDOF)

\[ H(w) = \frac{X_1(w)}{X_2(w)} = FRF \]

\[ H(w) = FRF \]

(Avitable, 2003)
Generation
Fast Pressure Sensors
High Pressure Port
(1200rpm, 200 bar)

\[ p_{\text{HP}} \text{ ripple (n1200p200b100)} \]

\[ p_{\text{HP}} \text{ FFT (n1200p200b100)} \]
Conclusion and Future Work

Conclusions

• Maha’s sound chamber has been successively remodeled.
• Preliminary measurements have been made to generate realistic data for analysis development.
• A few new analysis techniques have been highlighted

Future Work:
• Continue working on Analysis tools to fully map the oscillatory energy pathways.
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Thank You

Any Questions?