CENTER FOR COMPACT AND EFFICIENT FLUID POWER

A National Science Foundation Engineering Research Center

Marquette University | Milwaukee School of Engineering | Purdue University | University of California, Merced | University of Illinois, Urbana-Champaign | University of Minnesota | Vanderbilt University

Investigation of Noise Transmission through Pump Casing

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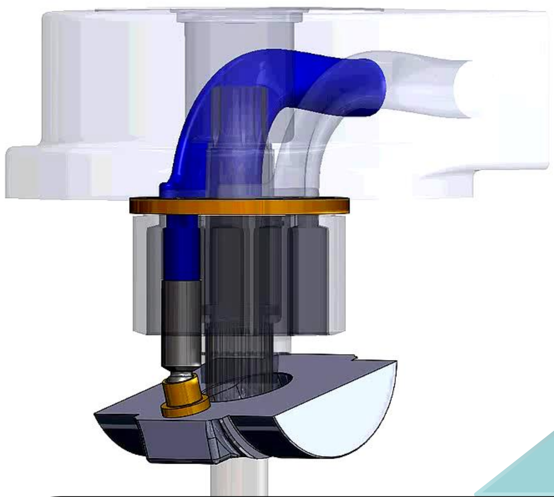
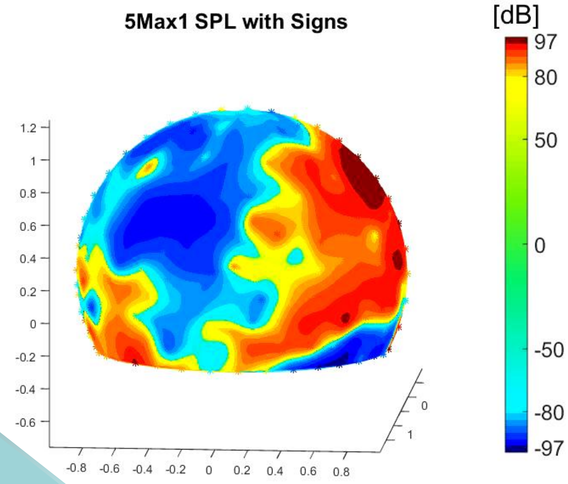
CCEFP Industry-University Summit

Lexington, KY | March 7 - 9, 2018

Structural Acoustic Paradigm



Structural-Acoustics

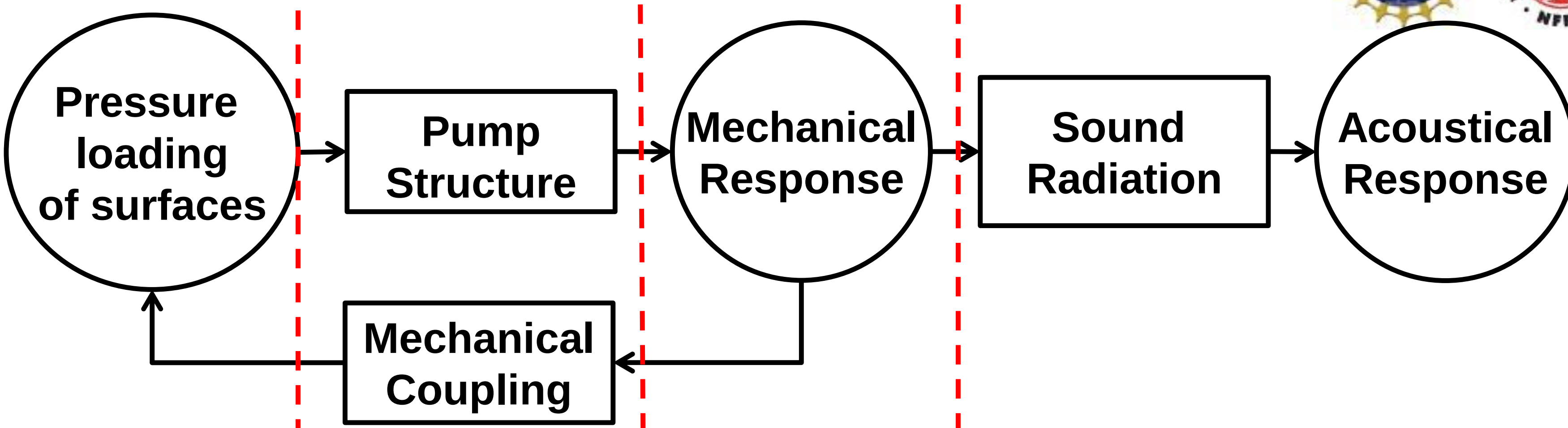


Pressure loading of surfaces → **Pump Structure** → **Mechanical Response** → **Sound Radiation** → **Acoustical** Response

Mechanical Response → **Mechanical** Coupling → **Pressure loading of surfaces**

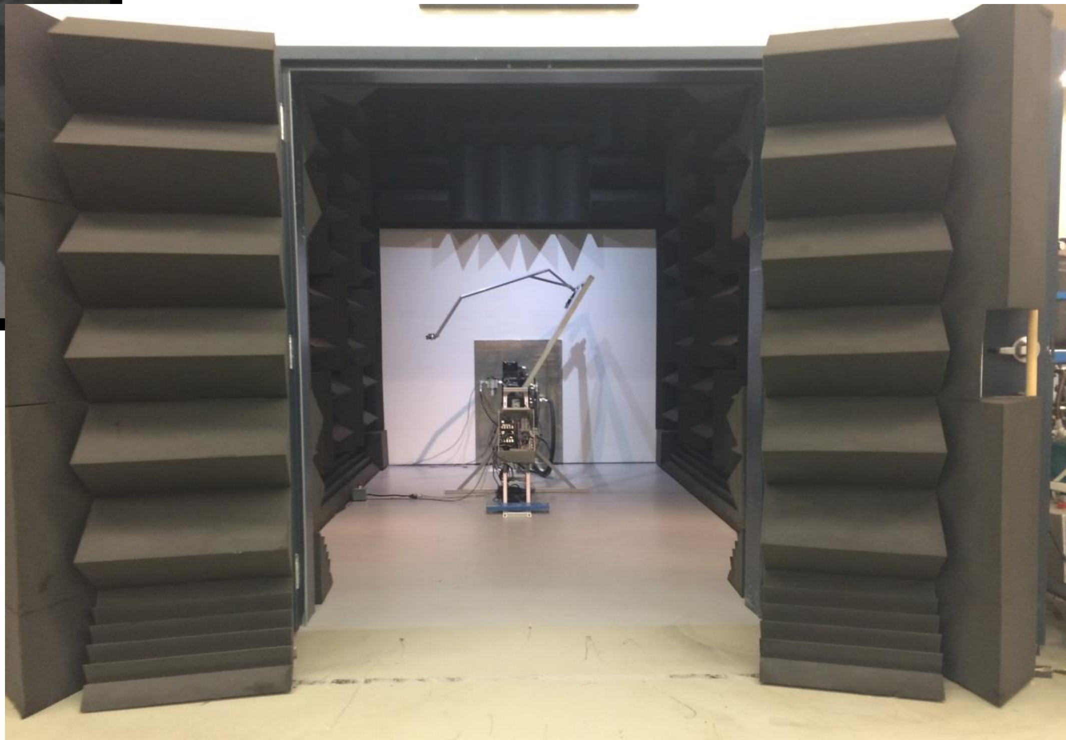
Generation | Transmission | Propagation | Radiation | Perception

Analysis Overview



Generation	Transmission	Propagation	Radiation	Perception
• Port pressures • Bore Pressure • Pressure Spectrums • Pressure Module sims	Empirical Transfer Functions	• Surface normal velocity field • Structural attenuation • Operational modal analysis	• Acoustic camera • Far-Field Spherical Harmonics	Sound pressure Intensity Sound Power ISO Loudness FFT 1/3 Octave
		Near-field holography		

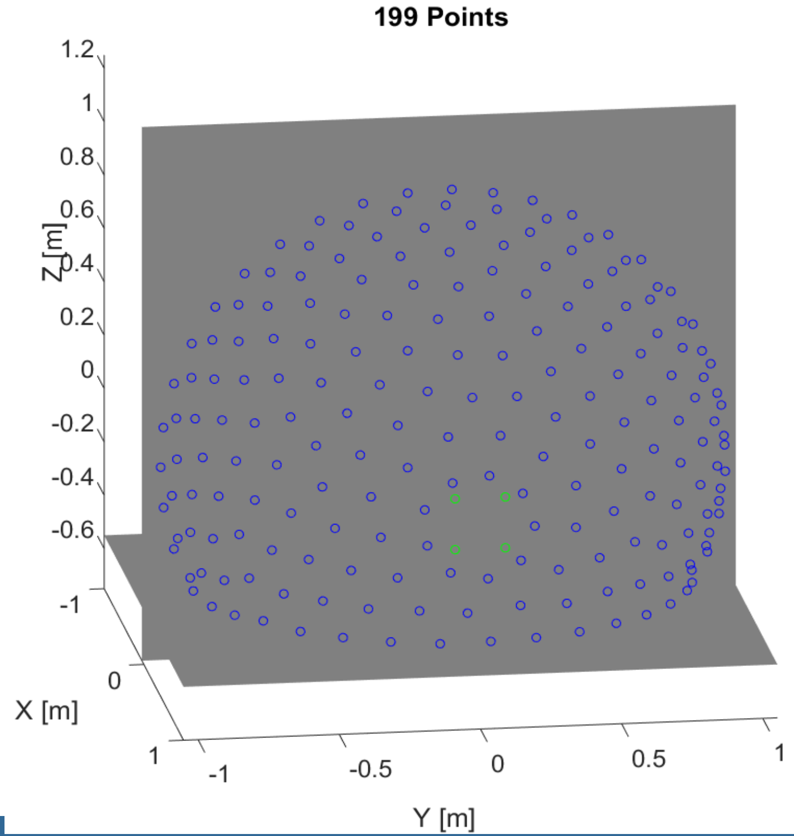
Experimental Facilities

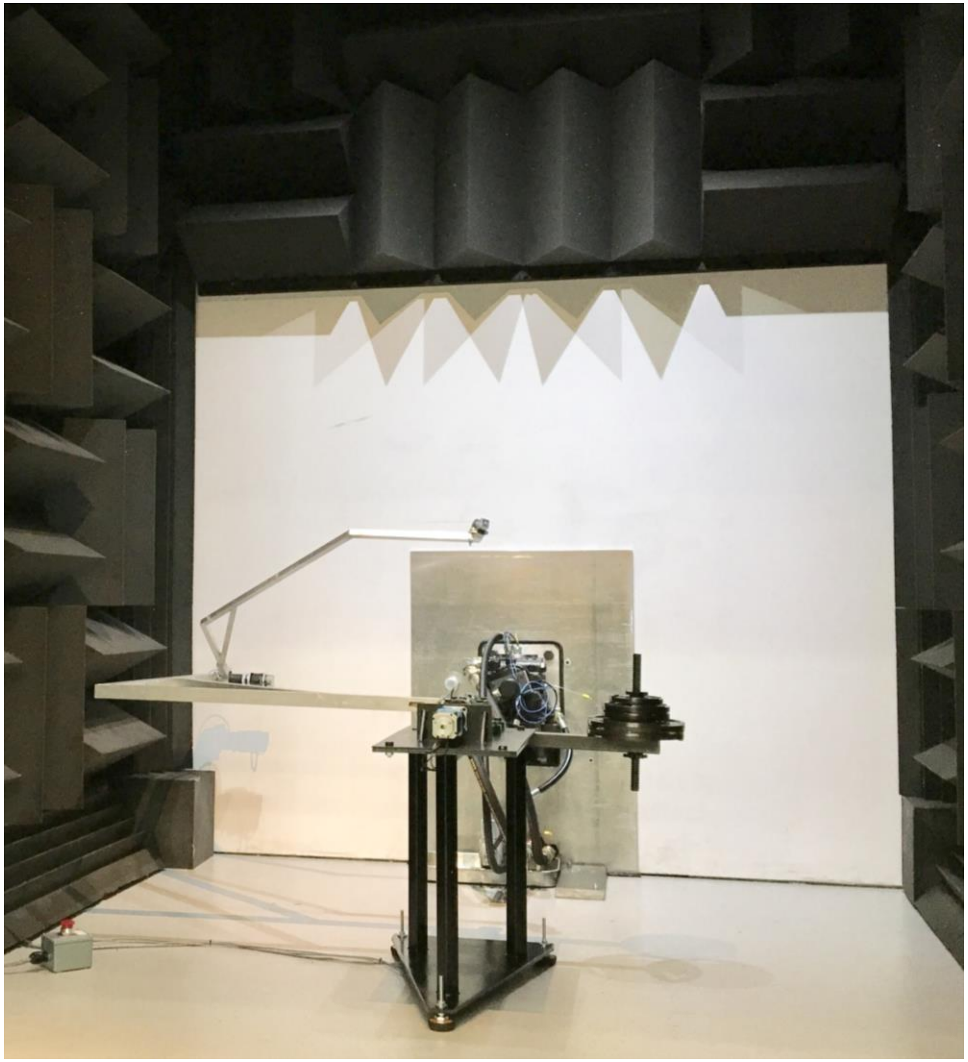


Characterize the measured sound field in spatial, temporal, and frequency domains.

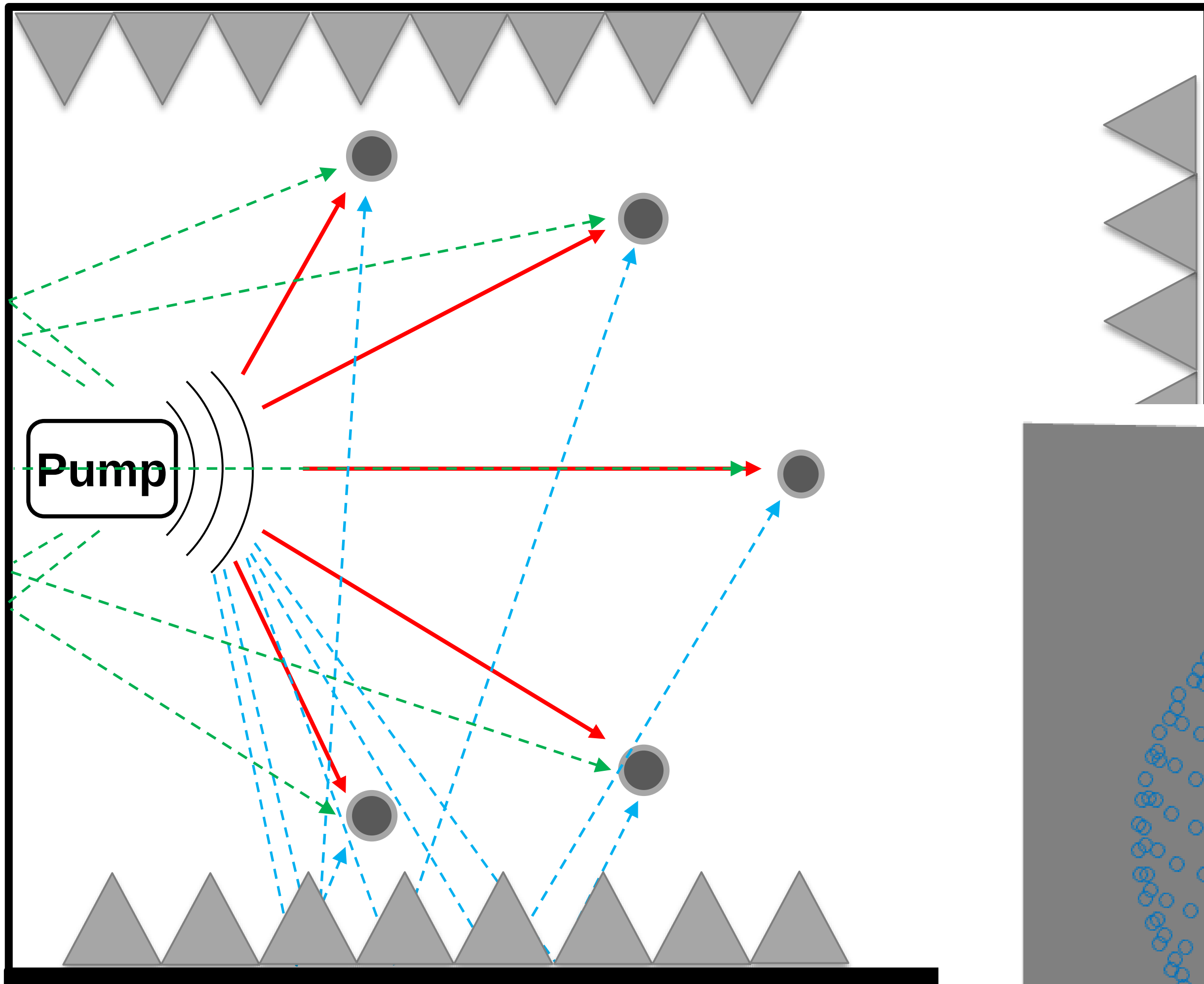
Automated Spatial Sampling

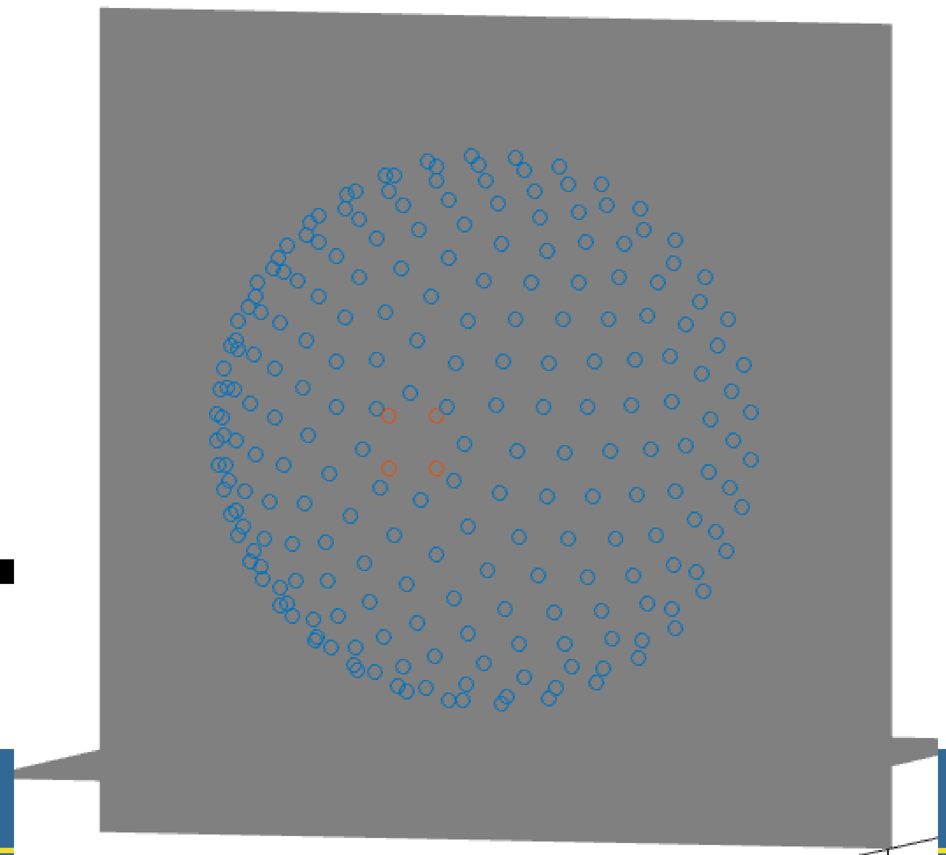
Custom robot for automated method of measuring sound intensity at any given number of evenly spaced locations.





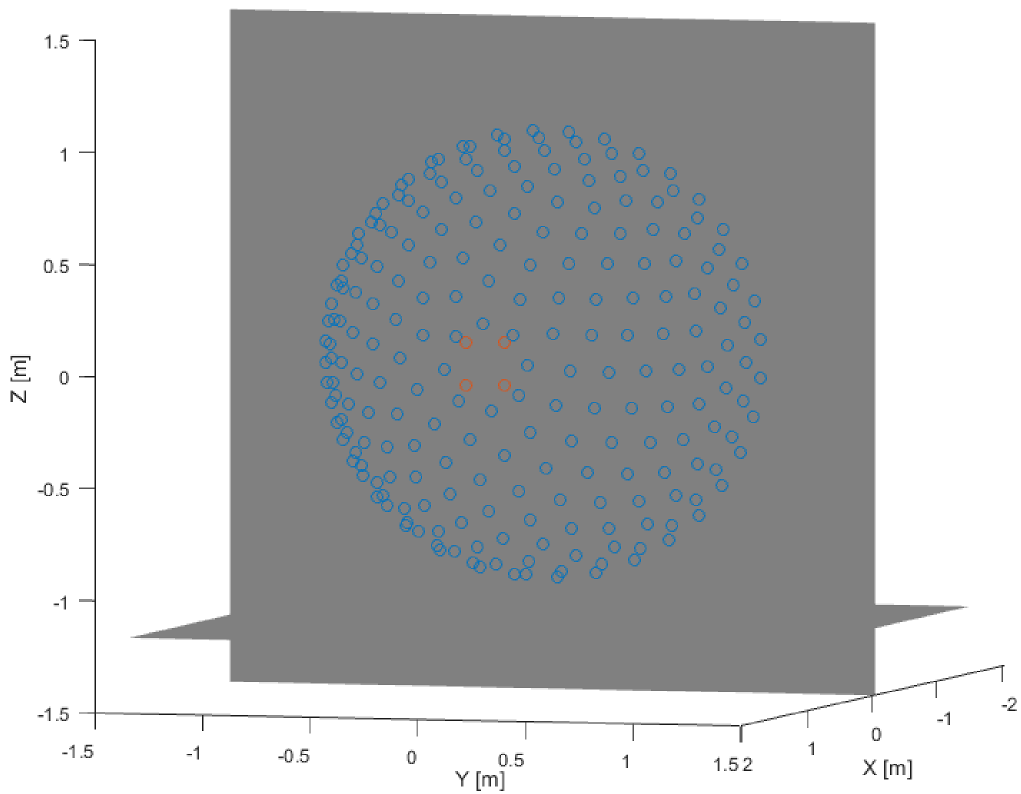
Floor Reflections Removal





Final Grid and Path

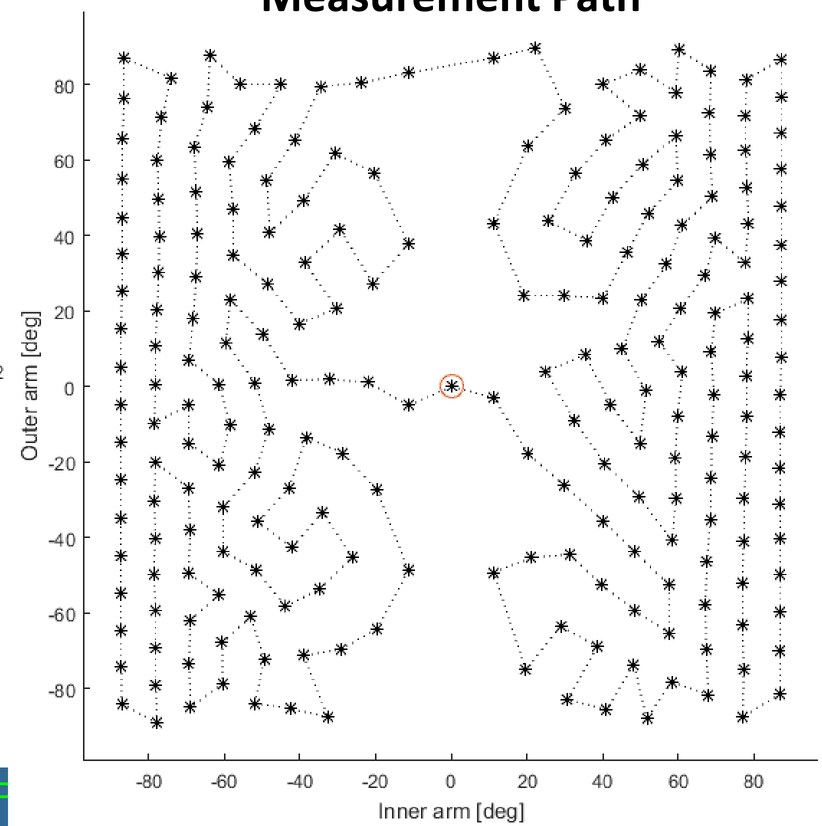
225-point Grid



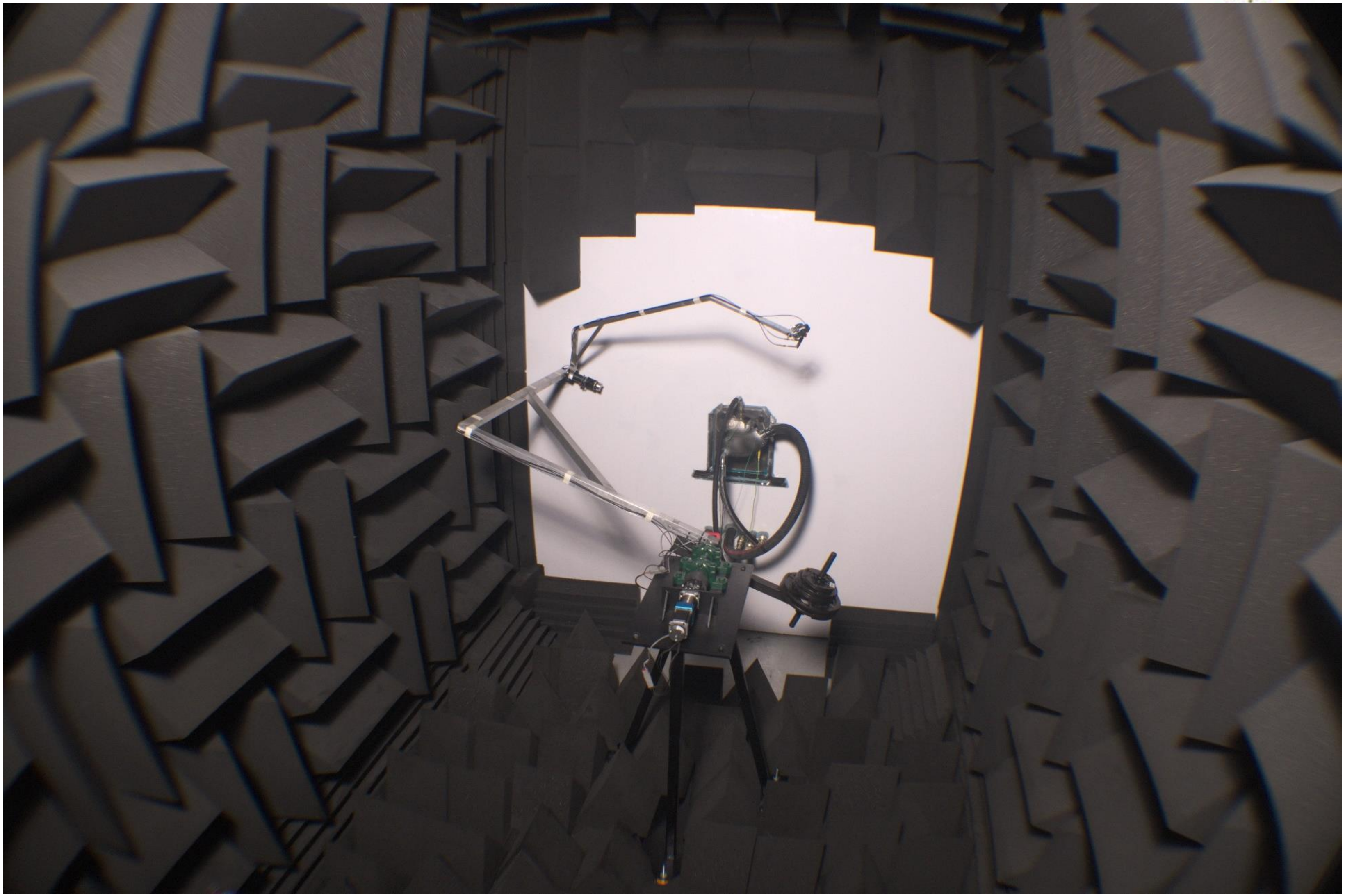
Hemispherical Grid:
- 225 points (26 more points)
- One reflection surface - fulfills ISO 4412

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

Measurement Path



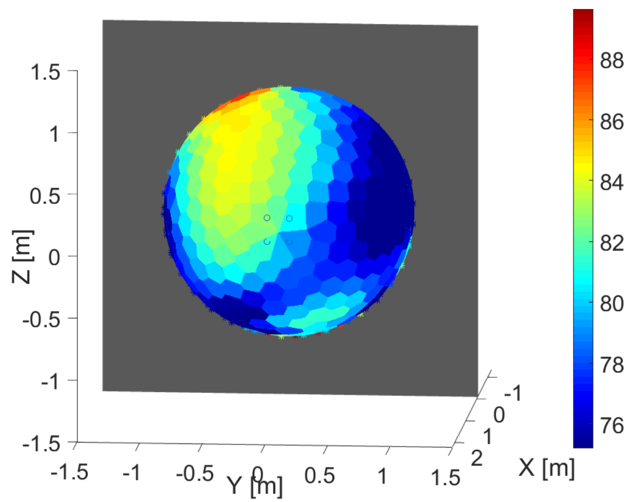
Updated Chamber



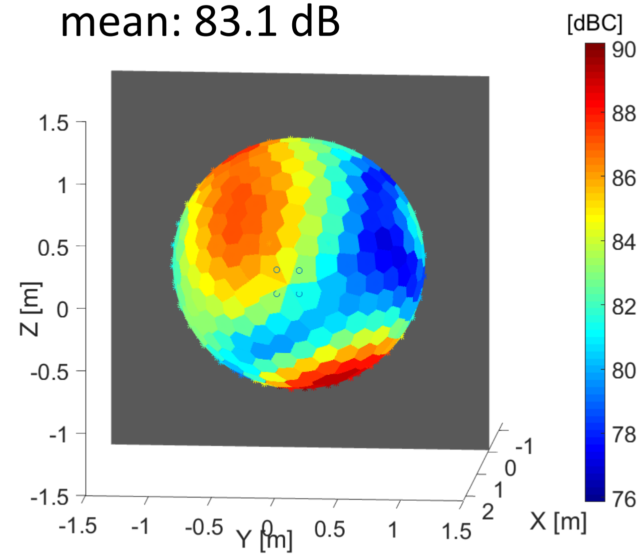
Perception

Example Perception Results

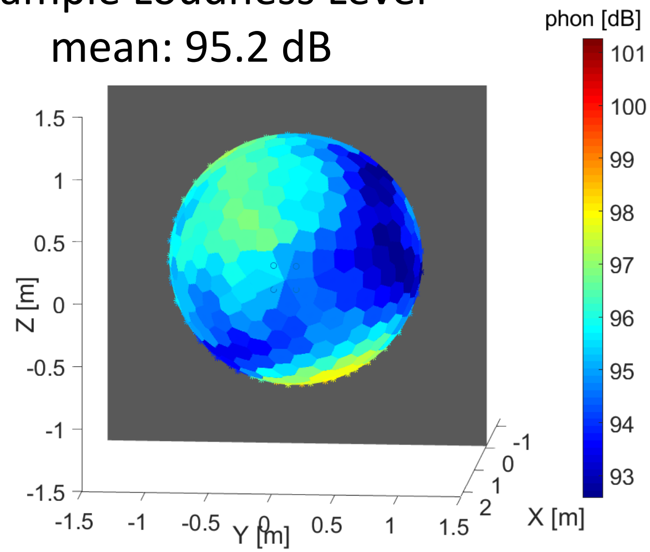
Example Sound Intensity Map
SWL: 86.1 dB



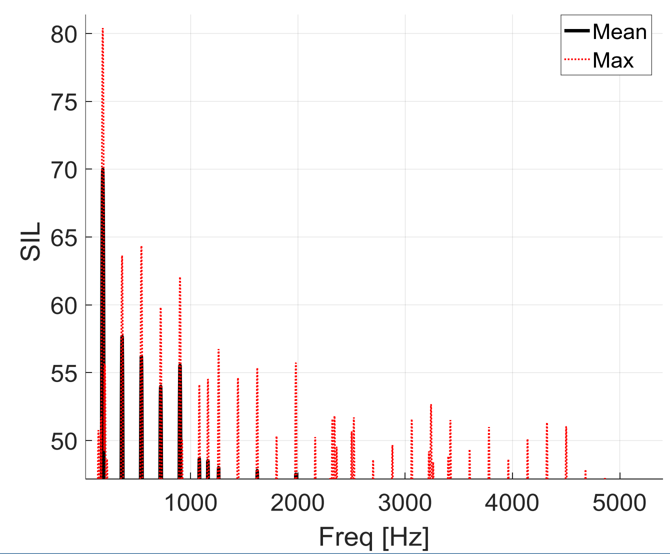
Example spl Level [dBc]
mean: 83.1 dB



Example Loudness Level
mean: 95.2 dB



Example Intensity FFT

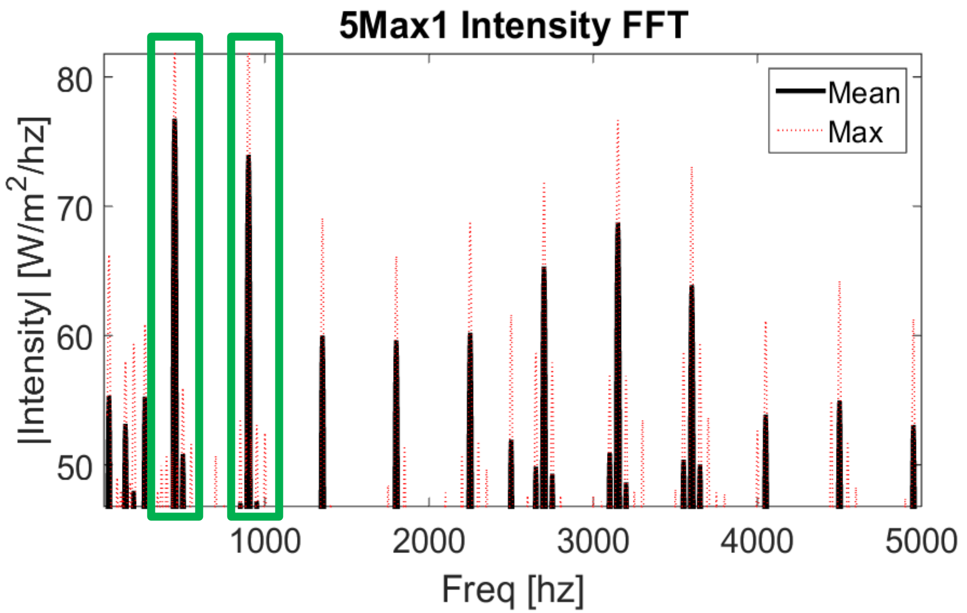


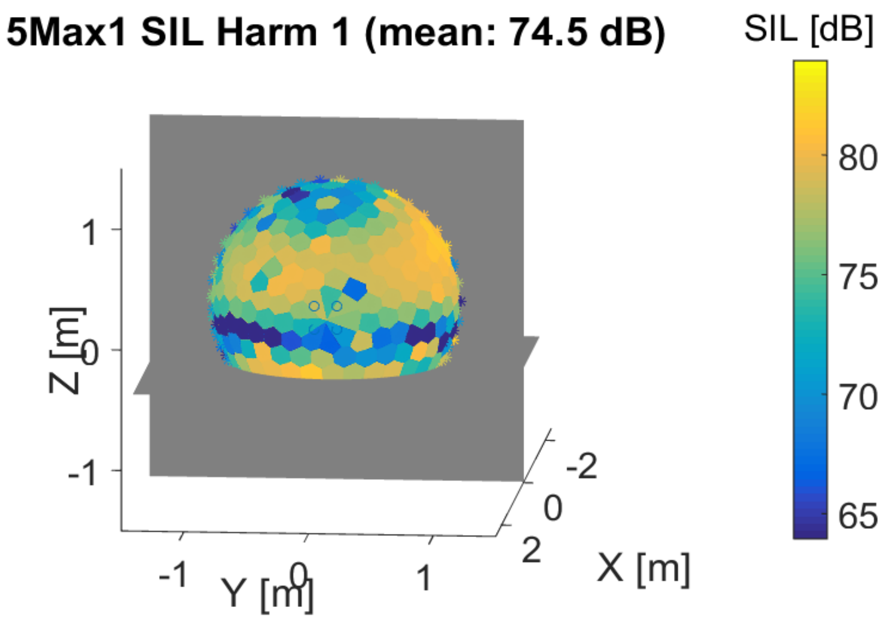
Frequency Analysis

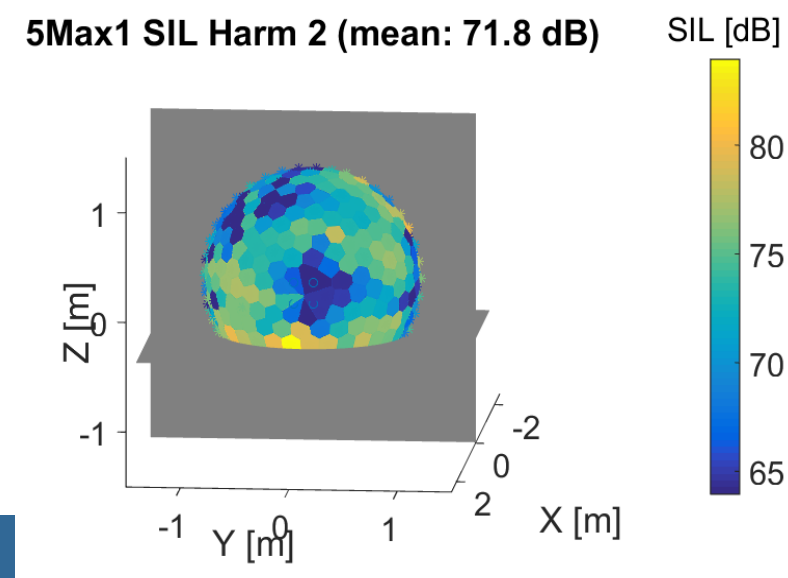
Example measurement:

A pump with 9 pistons @ 3000 rpm

Pump Harmonic Frequencies:
450 Hz, **900** Hz, **1350** Hz, **1800** Hz …





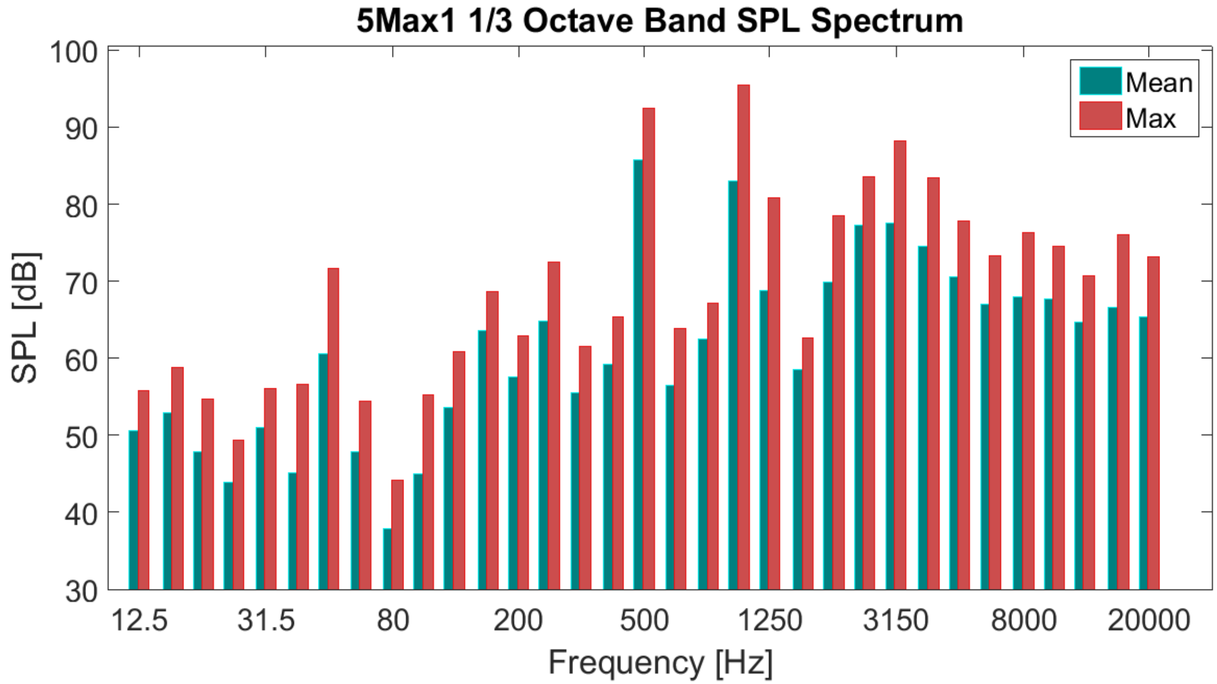


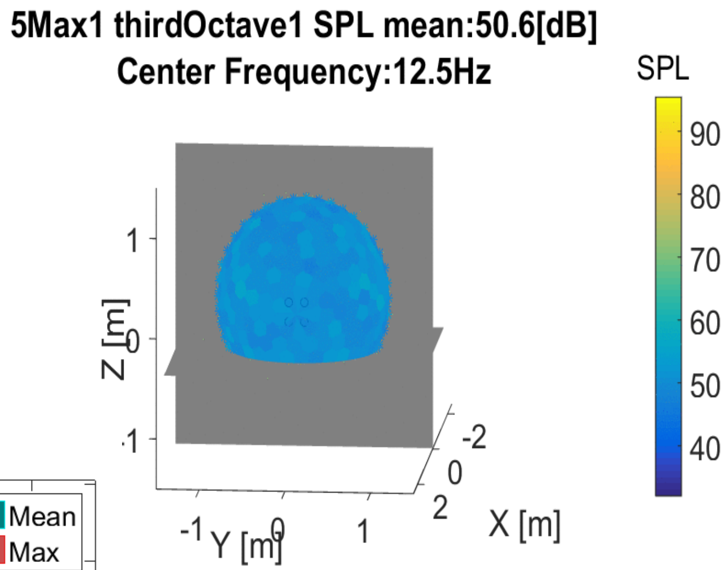
Frequency Analysis

Simplify the frequency analysis

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

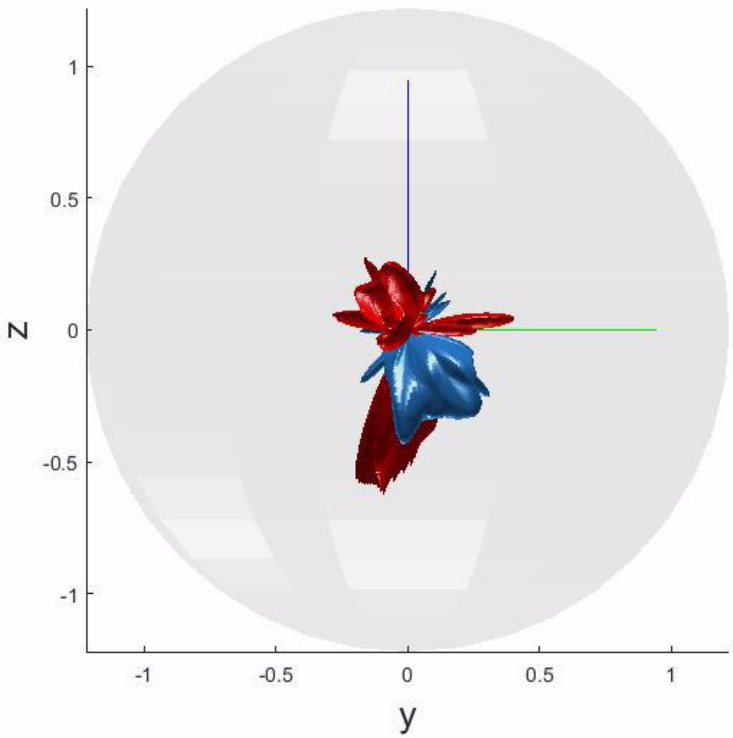
1/3 Octave: upper band frequency is the lower band frequency multiplied by $\sqrt[3]{2}$

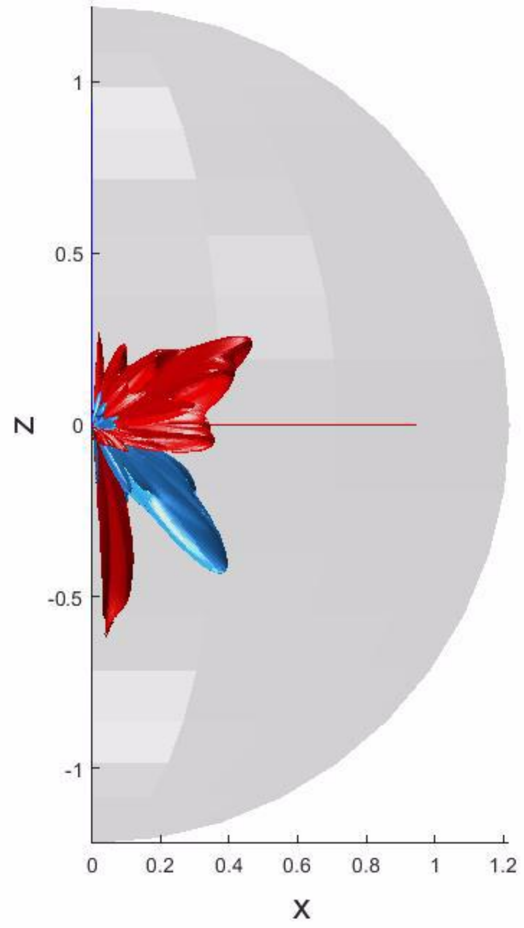




Spherical Harmonics
(radiation)

Measured Pressure Field
(1200rpm, Frequency: 0-25kHz)

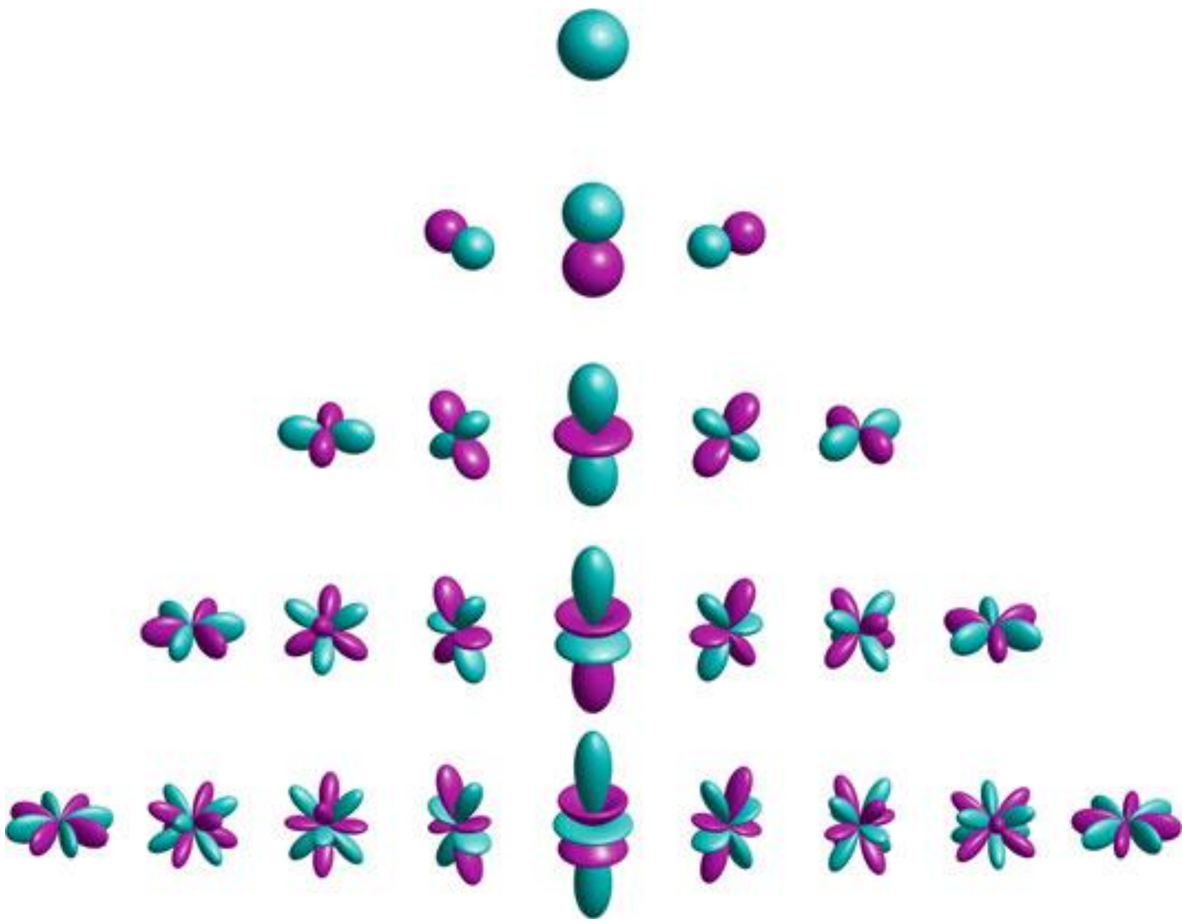




Acoustic Holography

Reconstruct the sound field; for **every location** and **any time**

1. Particle velocity
2. Sound pressure

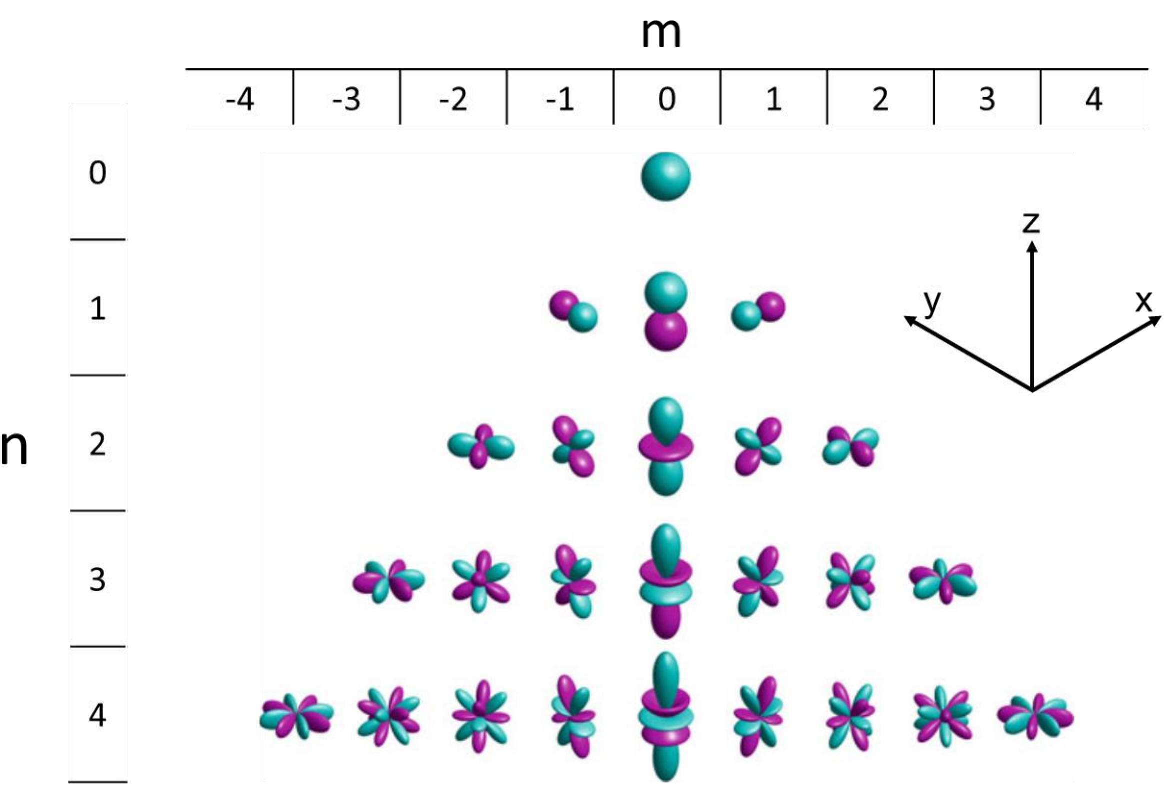


Consequentially:

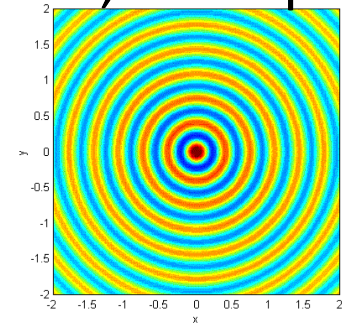
1. Modal vibrational pattern
2. Vector intensity field
3. Far-field radiation pattern
4. Total radiated power

(DeVries ,1994)

Acoustical Meaning of S.H. Functions

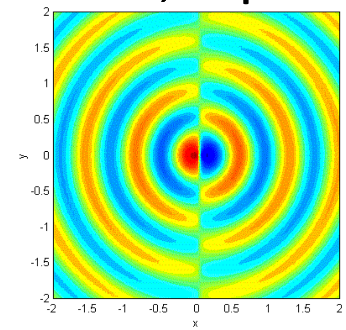


n = 0, monopole



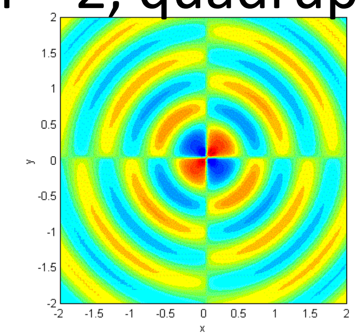
Pulsating sphere

n = 1, dipole



Pulsating force

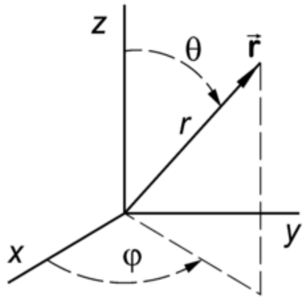
n = 2, quadrupole



Pulsating moment

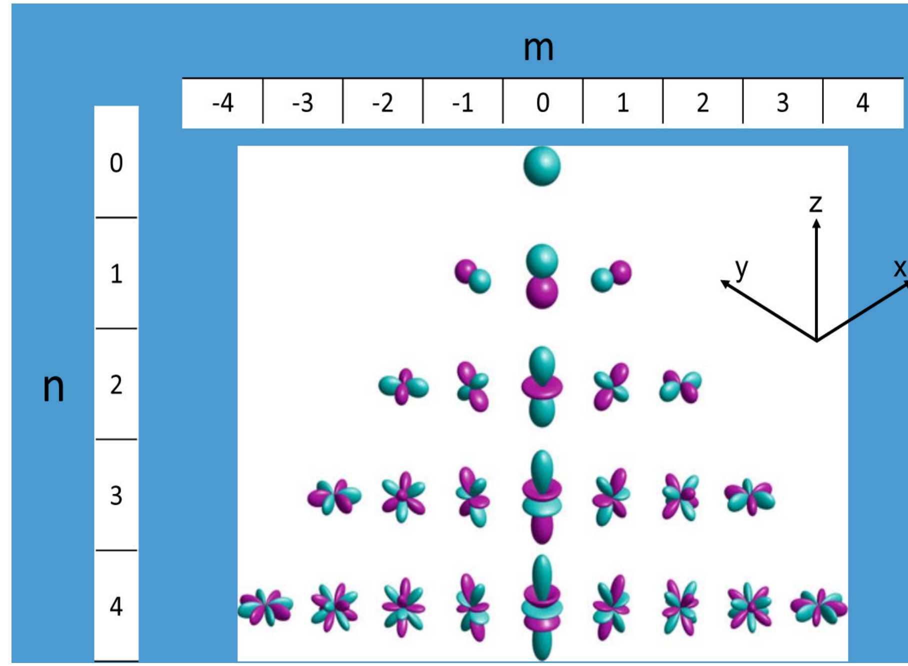
Wave Equation Decomposition

$$\nabla^2 \mathrm{p} = \frac{1}{c^2}\frac{\partial^2 \mathrm{p}}{\partial t^2}$$



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

Spherical Harmonic Functions



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: $$\nabla^2 p + k^2 p = 0 \quad (3)$$

Boundary condition:

robot grid positions

M, measured sound pressure

$$At \quad \boldsymbol{r} = \begin{bmatrix} \theta_1 & \phi_1 & r_1 \\ \theta_2 & \phi_2 & r_2 \\ \vdots & \vdots & \vdots \\ \theta_M & \phi_M & r_M \end{bmatrix}, \qquad \boldsymbol{p} = \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_M \end{bmatrix}$$

Possible solution to (3) is: $$p = \sum_{n=0}^{+\infty} h_n(kr) \sum_{m=-n}^{n} a_{nm} \cdot Y_n^m$$

$$\boldsymbol{p} = \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_M \end{bmatrix} = c_1 \begin{bmatrix} Y_0^0(\theta_1, \phi_1) \\ Y_0^0(\theta_2, \phi_2) \\ \vdots \\ Y_0^0(\theta_M, \phi_M) \end{bmatrix} + c_2 \begin{bmatrix} Y_1^{-1}(\theta_1, \phi_1) \\ Y_1^{-1}(\theta_2, \phi_2) \\ \vdots \\ Y_1^{-1}(\theta_M, \phi_M) \end{bmatrix} + c_3 \begin{bmatrix} Y_1^0(\theta_1, \phi_1) \\ Y_1^0(\theta_2, \phi_2) \\ \vdots \\ Y_1^0(\theta_M, \phi_M) \end{bmatrix} + \cdots$$

Least Square Fitting

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

$(N+1)^2$ unknowns

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

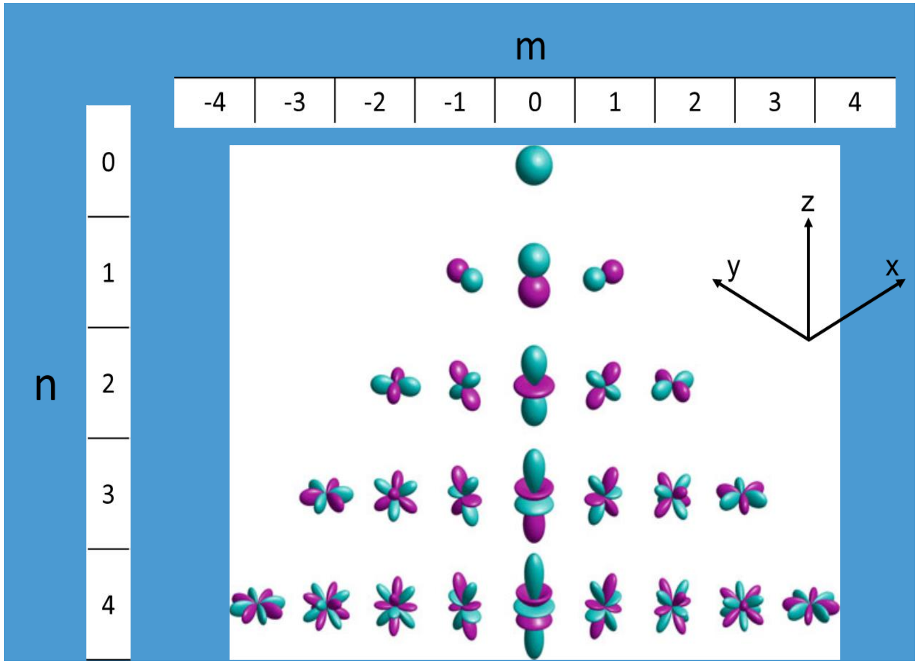
M equations

$$\boldsymbol{c} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_{(N+1)^2} \end{bmatrix}, \qquad \boldsymbol{p} = \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_M \end{bmatrix}$$

$$\boldsymbol{Yc} = \boldsymbol{p}$$

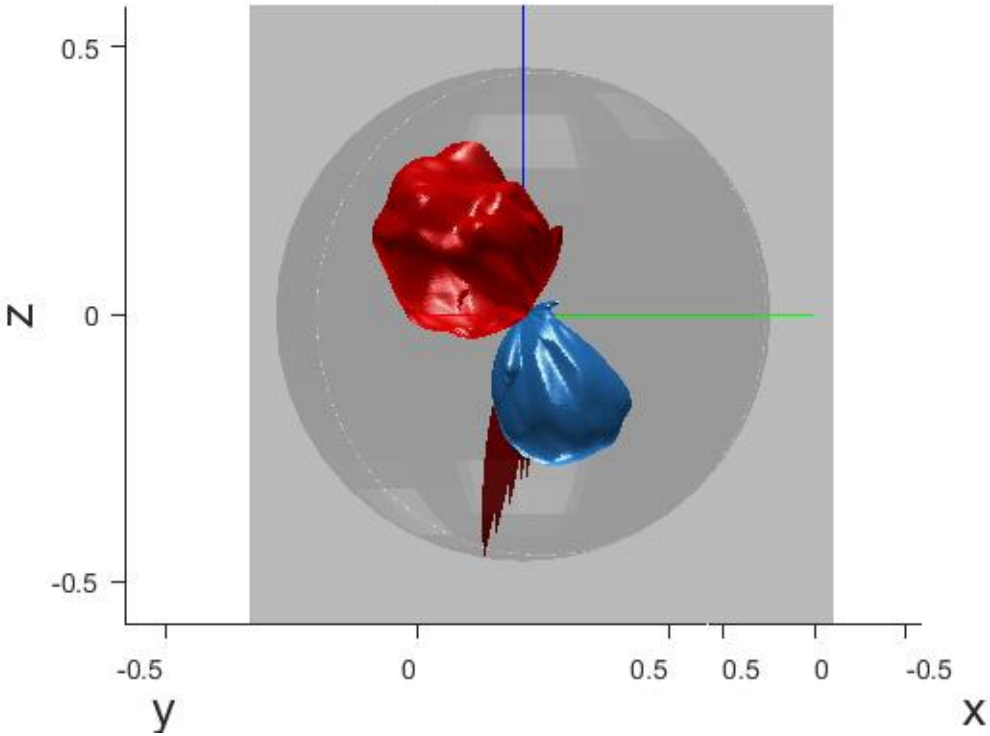
$$\boldsymbol{c} = \boldsymbol{Y}^{-1}\boldsymbol{p} \Leftrightarrow \boldsymbol{Yc} - \boldsymbol{p} = \boldsymbol{0}$$

$$\boldsymbol{c} = \boldsymbol{Y}^{+}\boldsymbol{p} \Leftrightarrow \boldsymbol{min}(\|\boldsymbol{Yc} - \boldsymbol{p}\|)$$

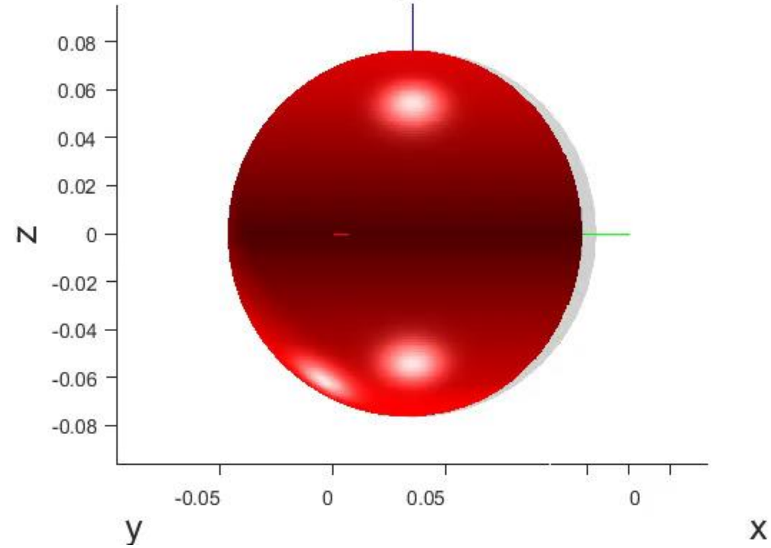


Measurement Fitting

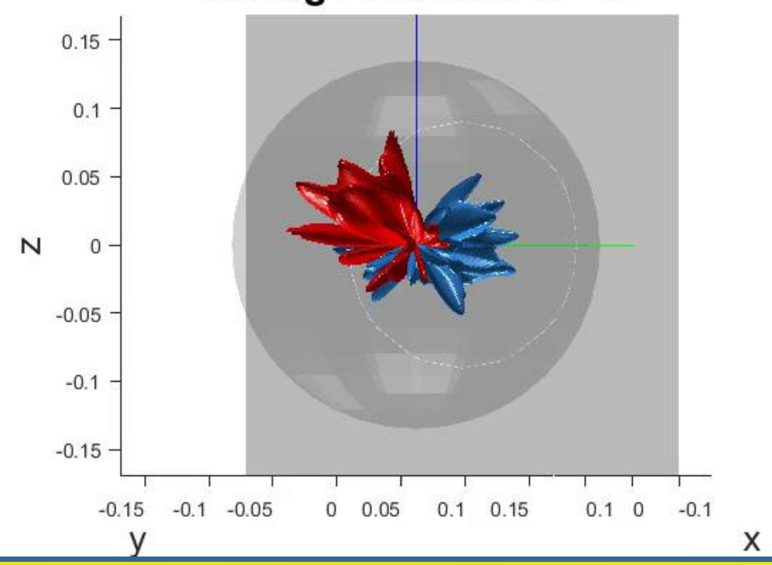
Measured Complex Pressure - 180 Hz



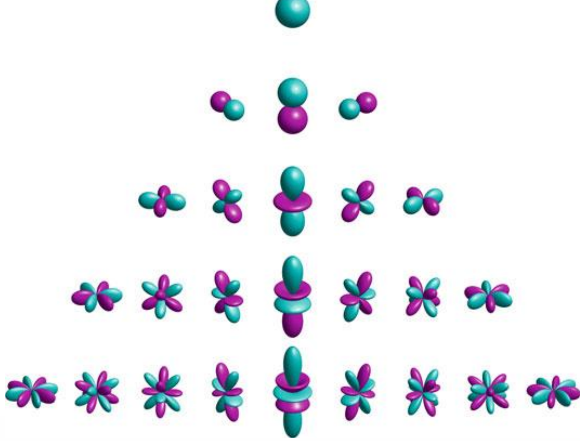
LS Fitting on N = 0

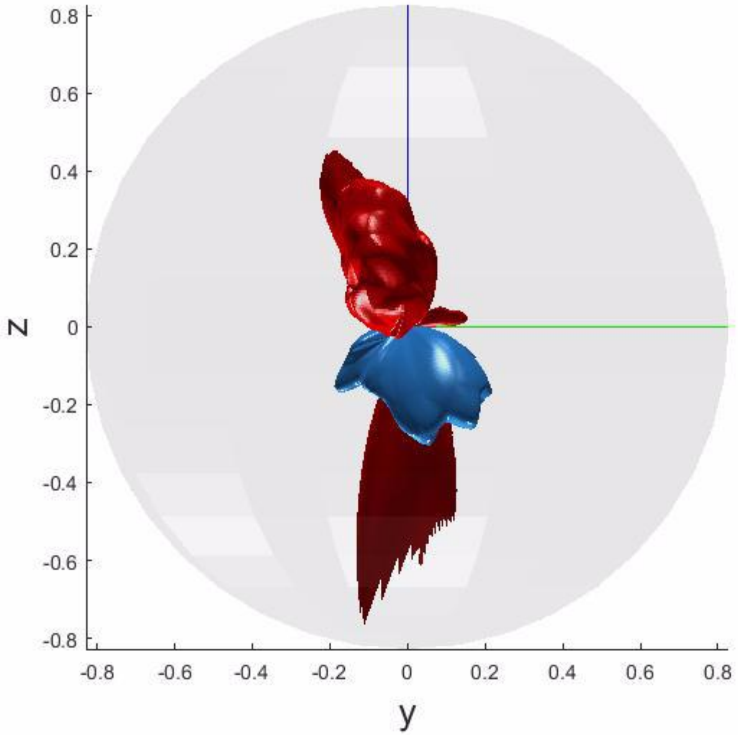


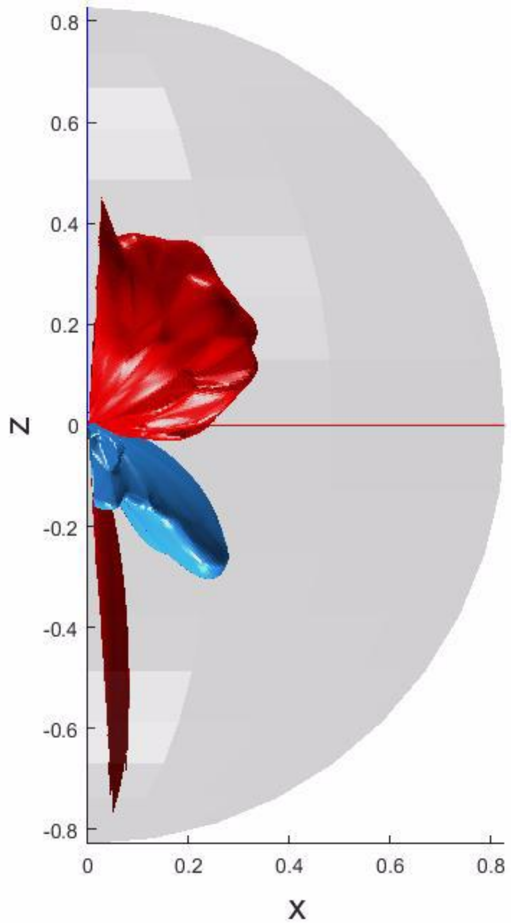
Fitting Errors on N = 0



Measured Pressure Field
1200rpm, 1st harmonic (180 Hz)







Measured Pressure Field

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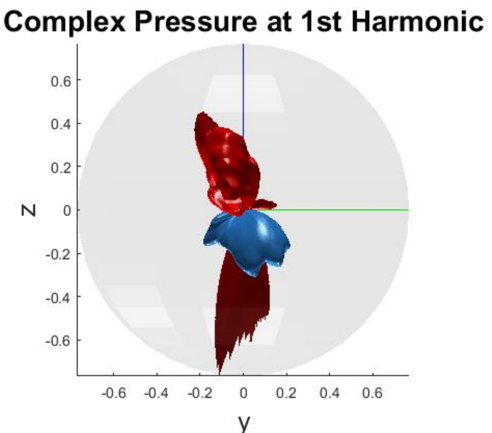
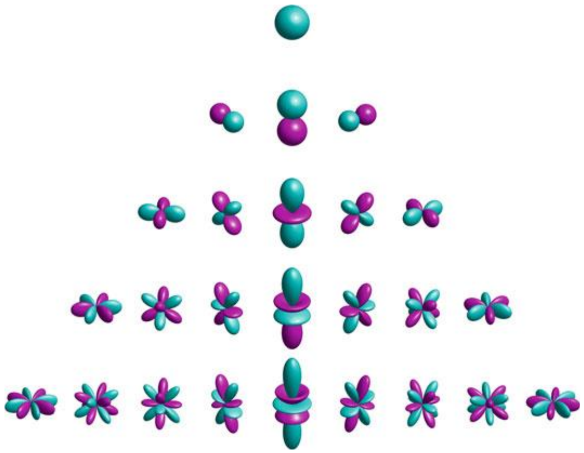
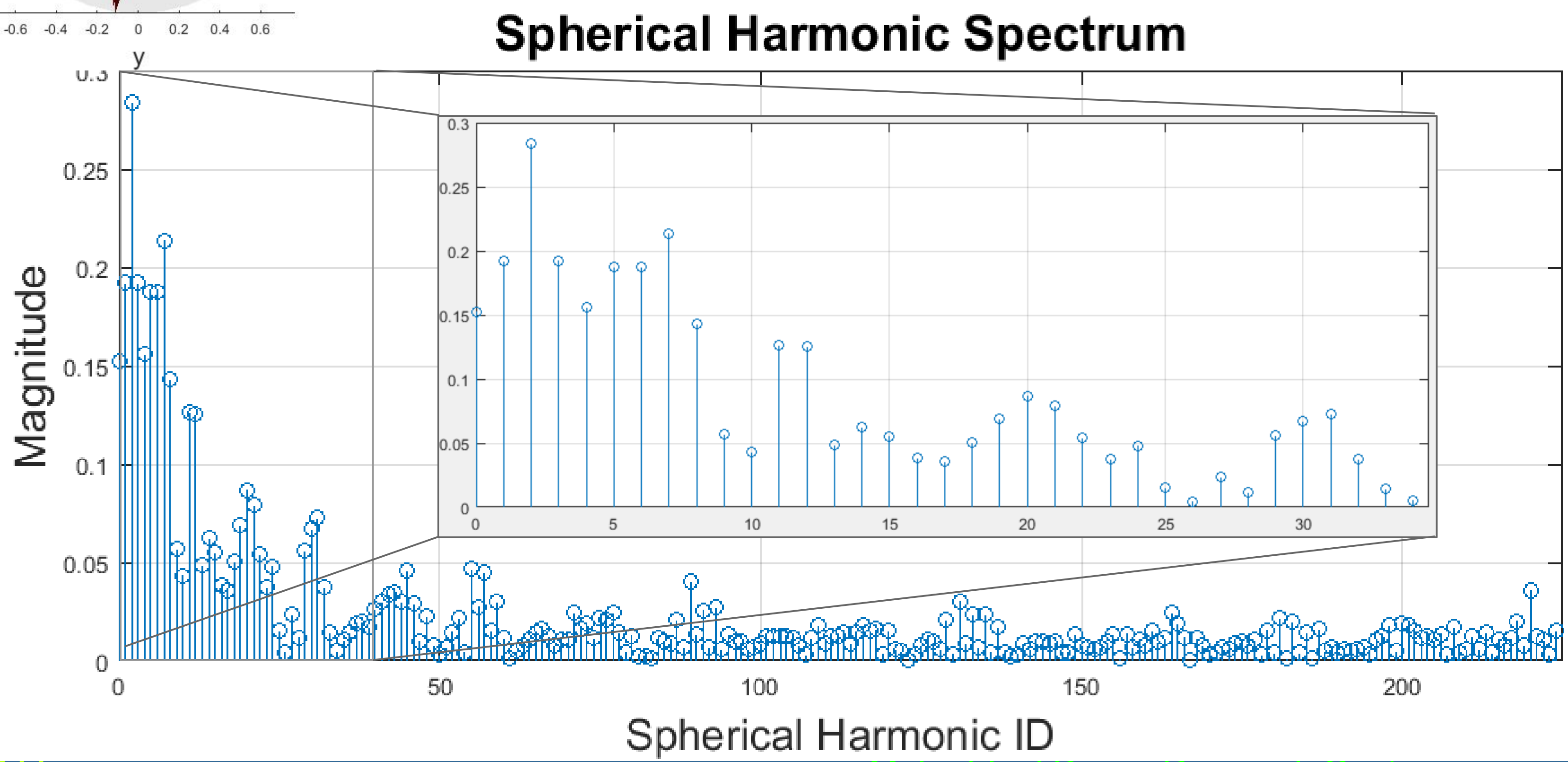
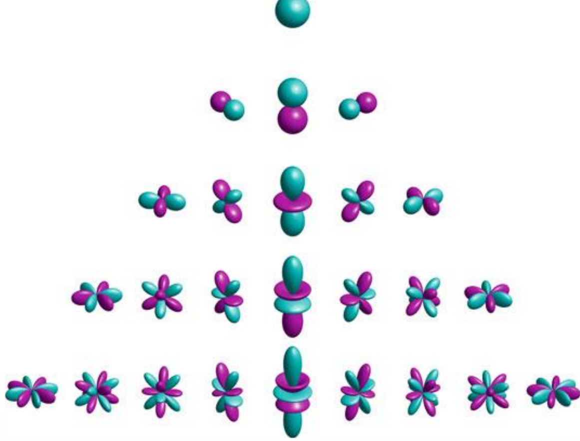


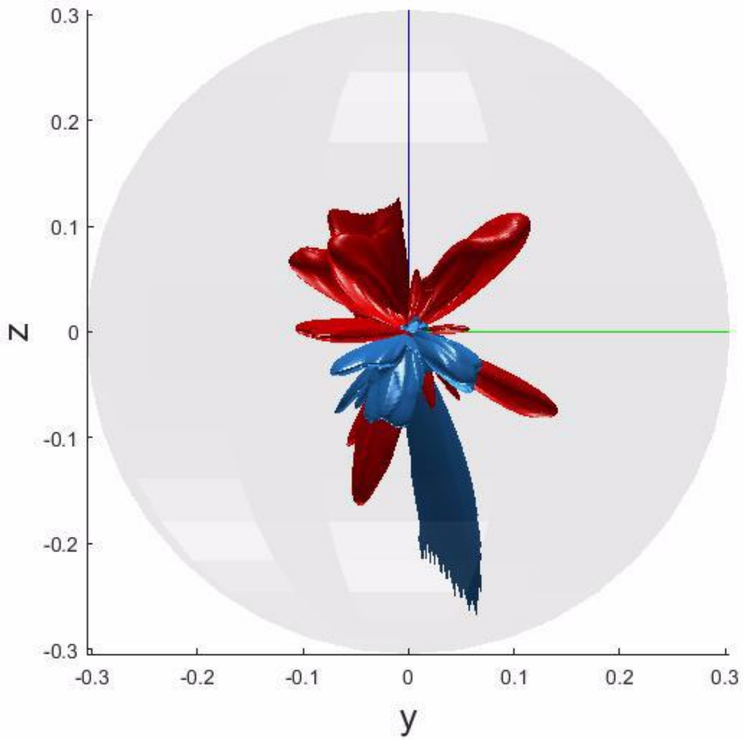


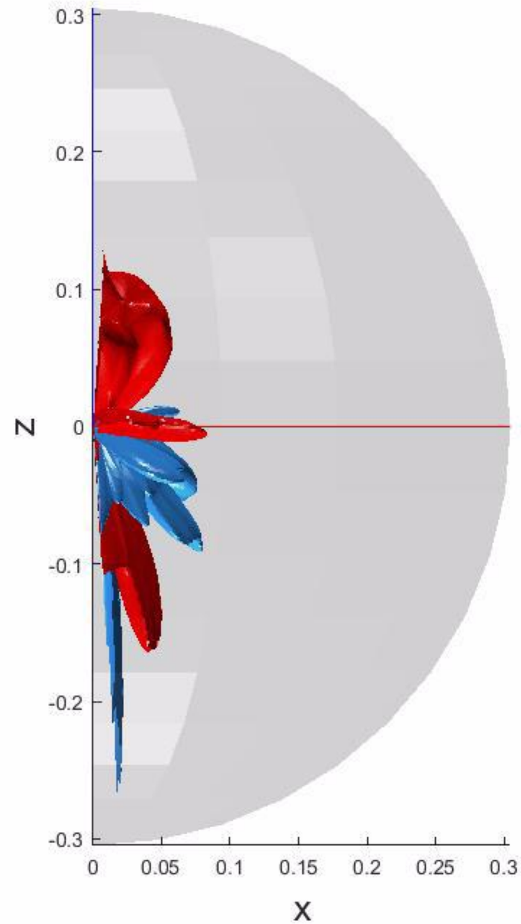


Measured Pressure Field

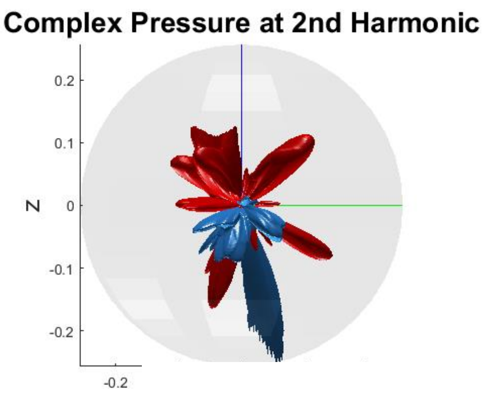
2400rpm, 2nd harmonic (720 Hz)

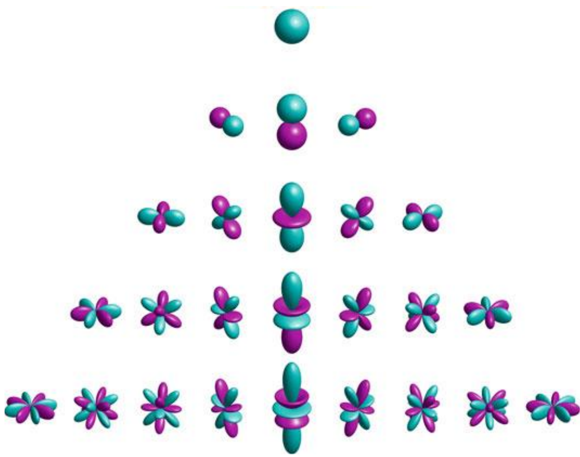


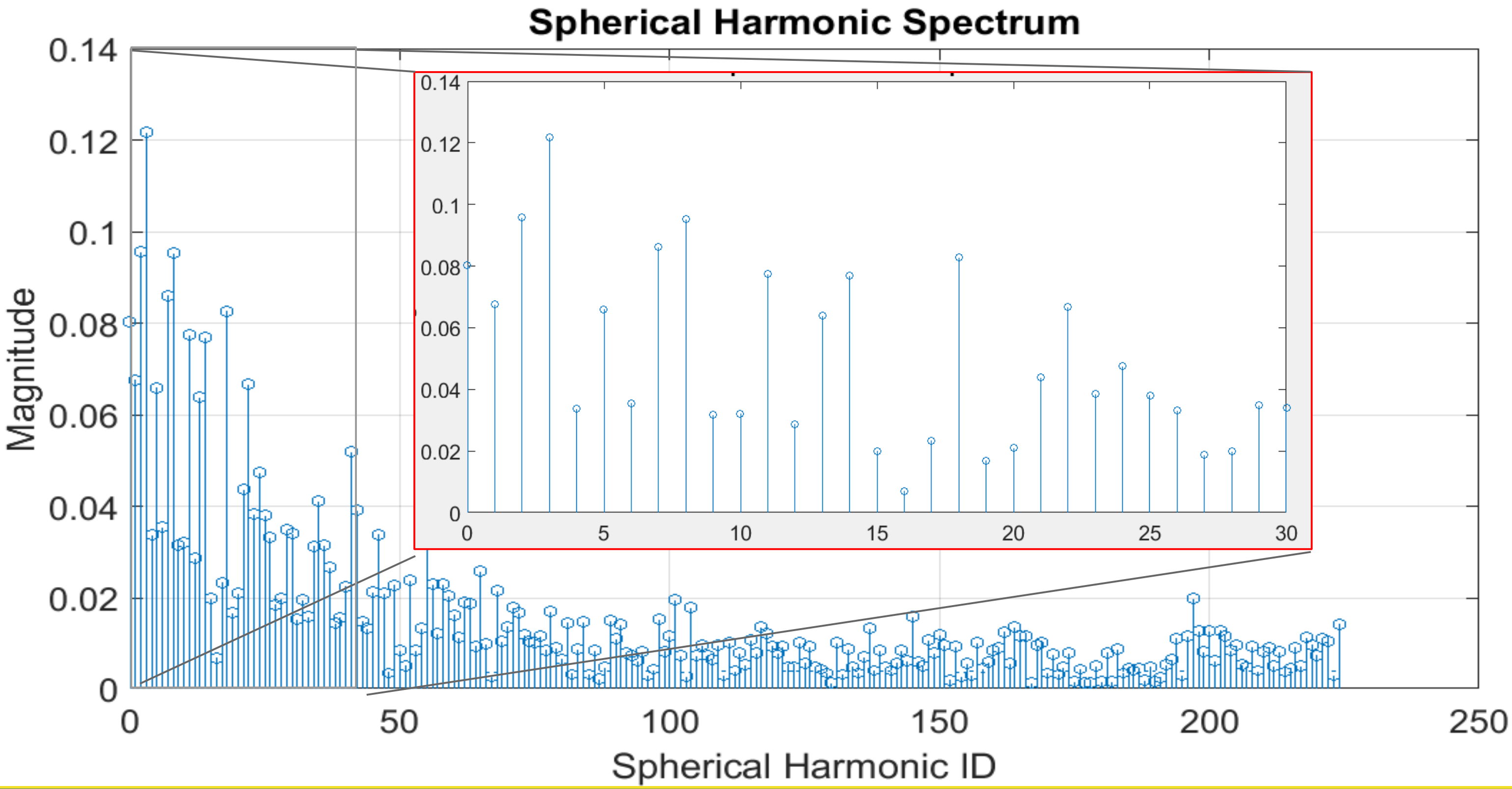




Measured Pressure Field
2400rpm, 2nd harmonic (720 Hz)

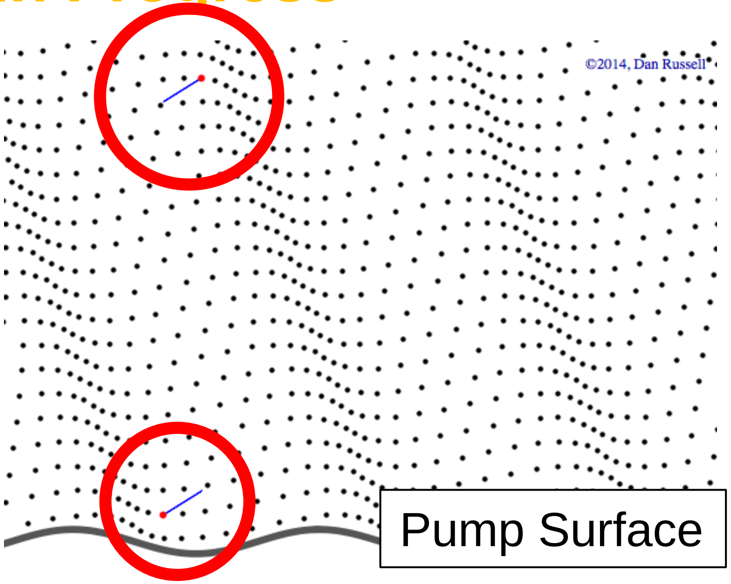


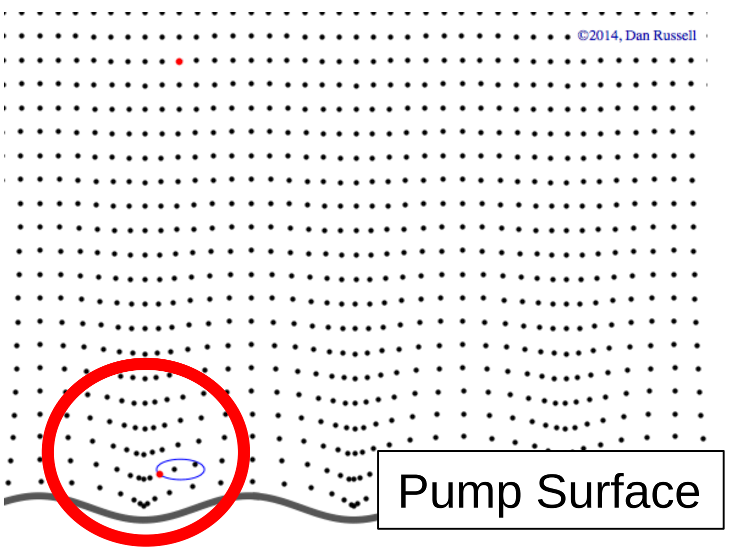




Near-Field Holography

In Progress





Far-field holography capture's only the propagating pressure waves

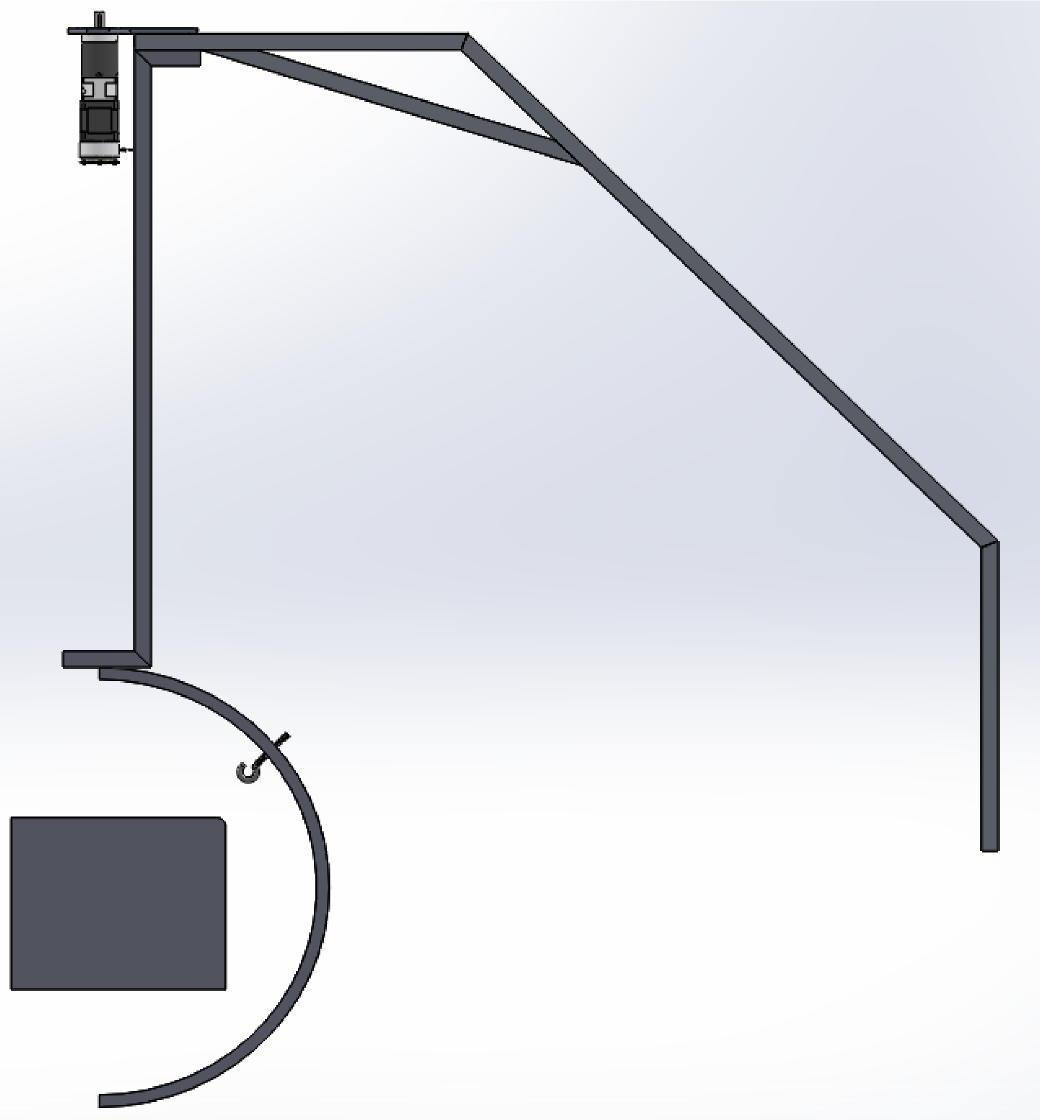
The pressure field also includes **Evanescent waves,** which decay exponentially with distance.

Near-field holography capture's both the propagating and evanescent waves

Paul Kalbfleisch
Maha Fluid Power Research Center

Near-Field Arm

In Progress



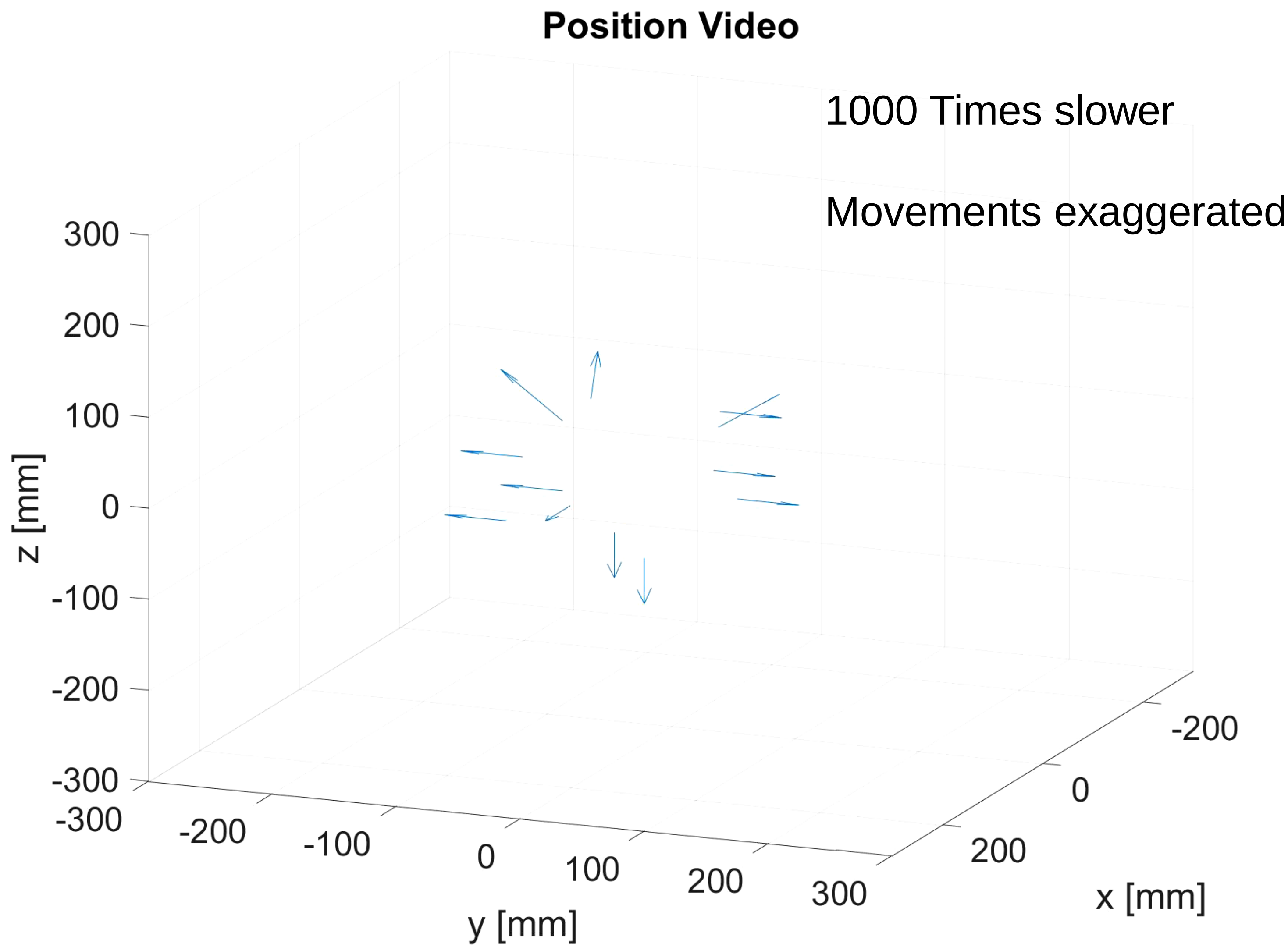
A near field arm is being manufactured.

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

- Easier / faster
- Repeatable

Propagation

Surface Vibrations Example 1200rpm



Structural Attenuation

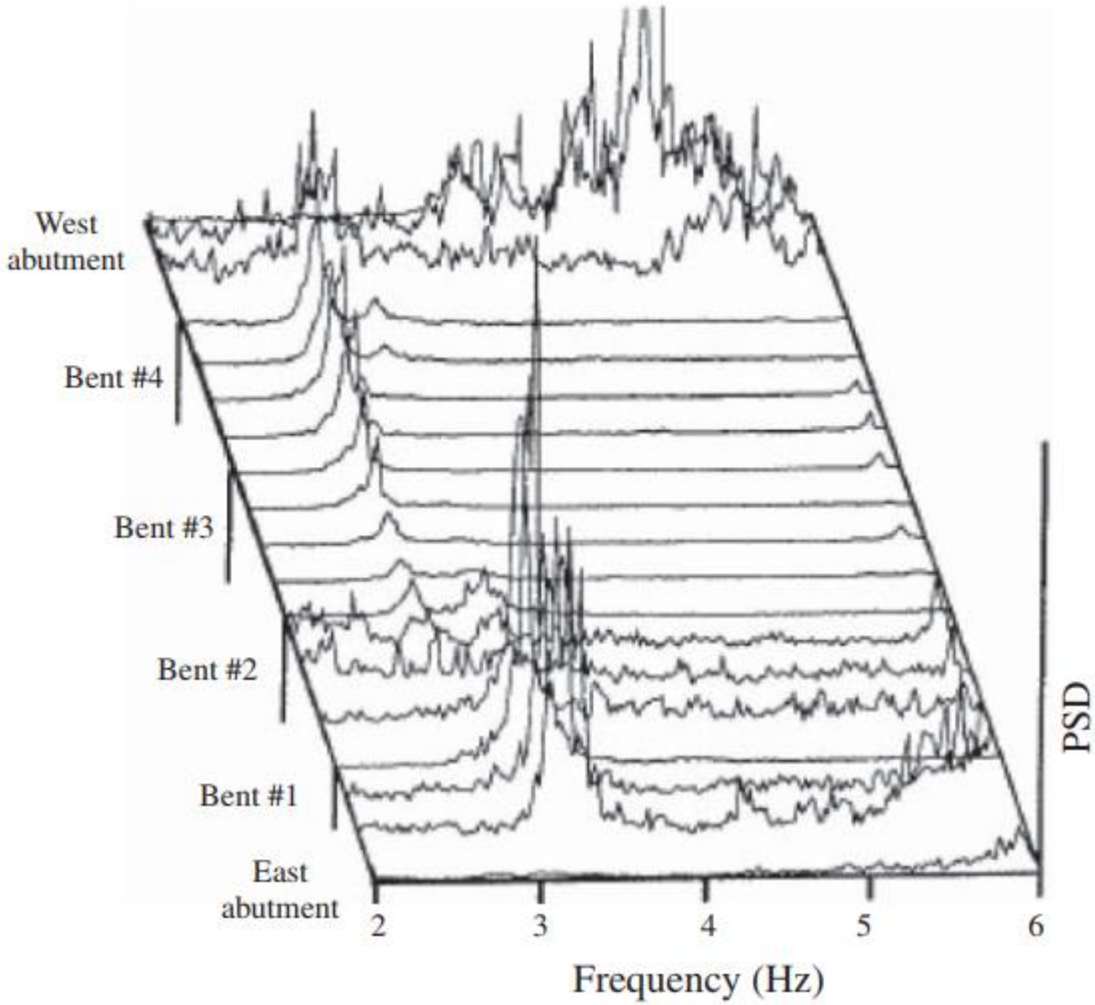
In Progress

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**

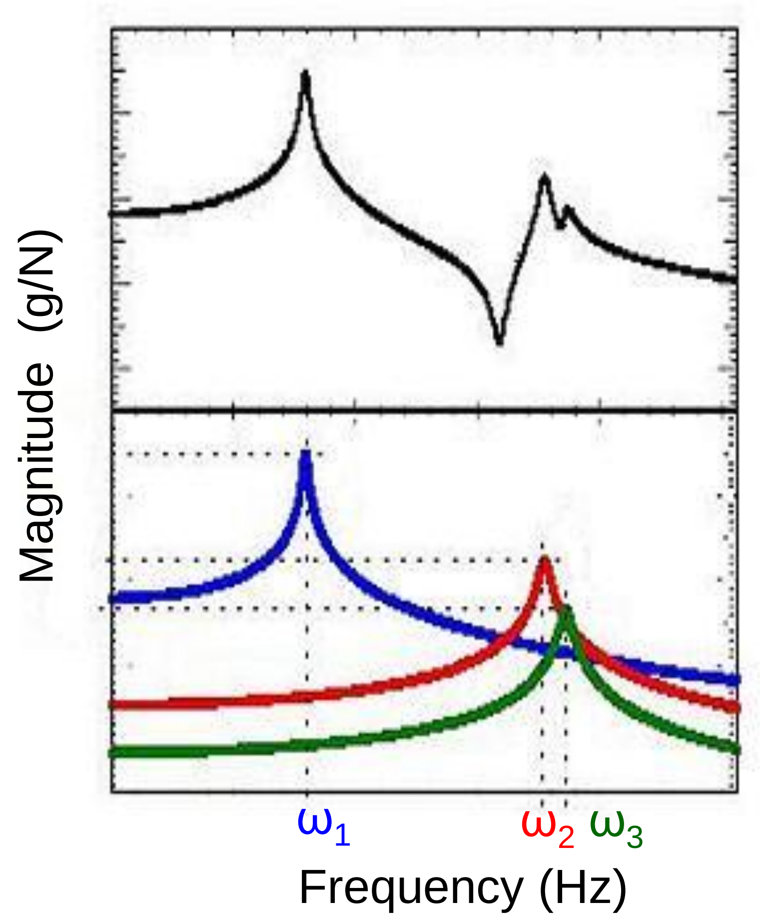


Operational Modal Analysis

- Basic Frequency Response Equation (SDOF)

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

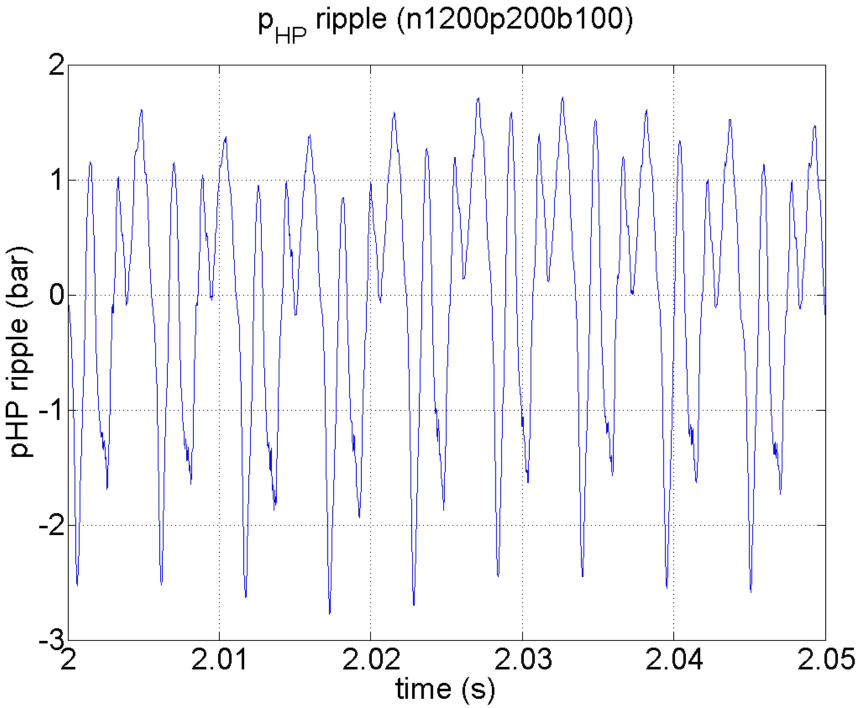
$$H(w) = \frac{\text{(sensor)}}{\text{(sensor)}} = FRF$$

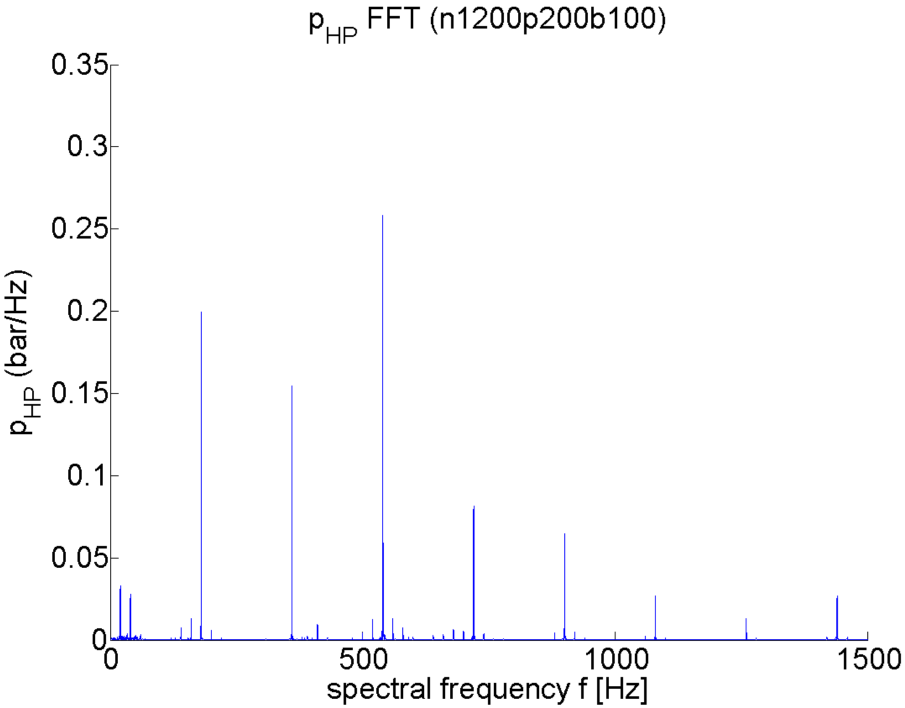


(Avitabile, 2003)

Generation

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





Conclusion and Future Work

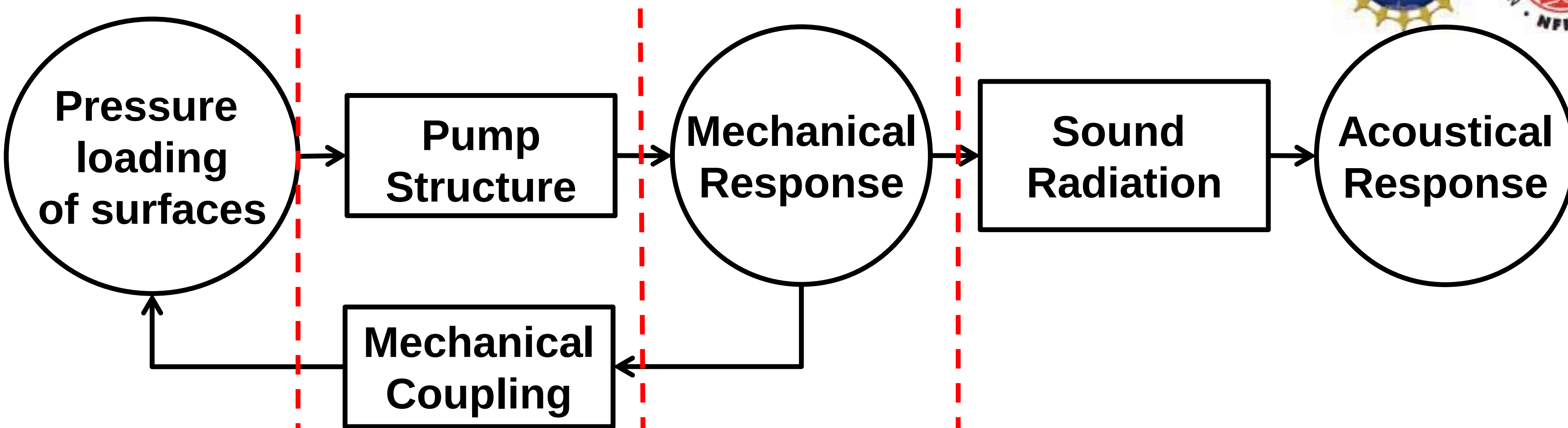
Conclusions

- 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.

Analysis Overview



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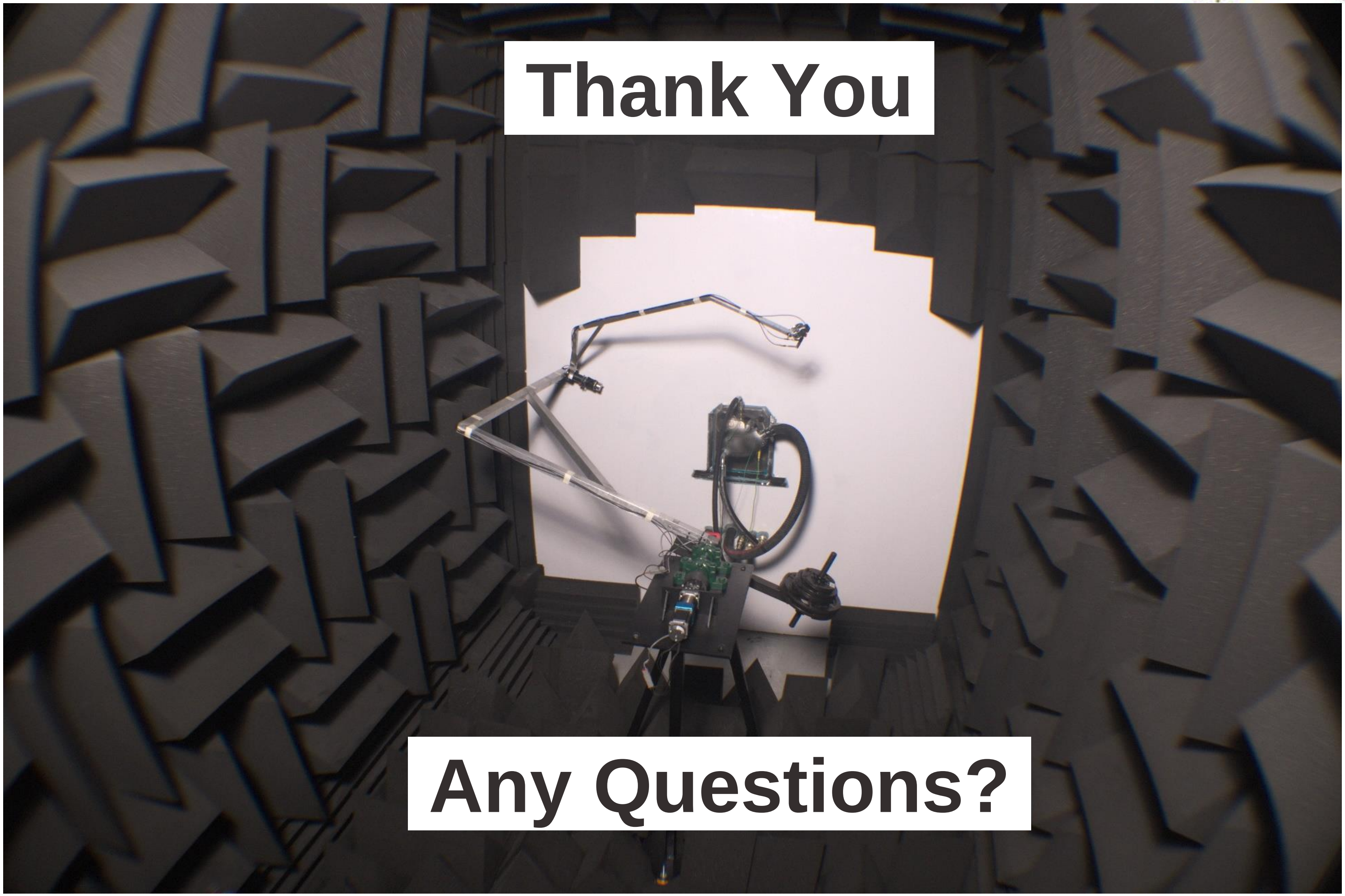
Thank You
Any Questions?