# Global Attenuation of Acoustic Fields Using Energy-Based Active Control Techniques

Scott D. Sommerfeldt

Acoustics Research Group
Brigham Young University

November 17, 2009

BYU Acoustics

# Acknowledgments

- Kent Gee – BYU
- Ben Faber – BYU
- Brian Monson – BYU
- David Copley – Caterpillar, Inc.
- Buye Xu – BYU
- Ben Shafer – BYU
- Connor Duke – BYU
- Cole Duke – BYU
- Matt Green - BYU

BYU Acoustics

# Outline

- Local vs. global control – identifying ANC objective
- Global control concepts
  - Free field radiation
  - Enclosed sound fields
- Implementation of global control
  - Free field radiation
  - Enclosed sound fields
- Application results
  - Global control of axial fan noise
  - Global control of cab noise in heavy equipment

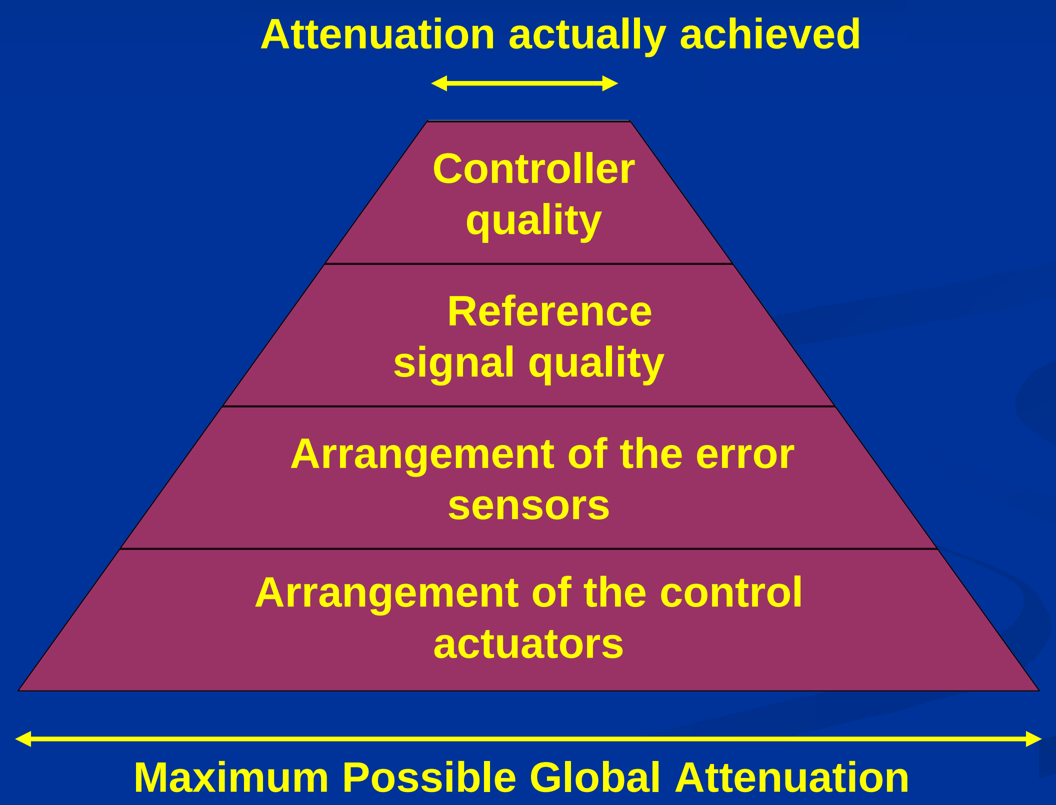


BYU Acoustics

# Local vs. Global Control

- Exactly what are we  trying to accomplish?
  - Does local control meet my objective?
  - Do I need a global solution?
- If objective not kept in mind, probability is high that one will not accomplish desired outcome
- If global control desired for application, energy in the field must be minimized
  - Implications of how this is done vary by application

# Hierarchy of Active Control (Snyder, Hansen)



# Global Control – Free Field Radiation

- Physical mechanism for global control is source coupling
  - Function of frequency and source spacing/location
- Need to minimize overall power (energy) radiated into field
- Concept easily seen for case of two monopole sources

$$\Pi = \frac{\rho c k^2}{8\pi} |Q_1|^2 \left[ 1 + A^2 + 2A \frac{\sin(kd)}{kd} \cos\gamma \right]$$

$$\Pi_{\min} = \frac{\rho c k^2}{8\pi} |Q_1|^2 \left[ 1 - \left( \frac{\sin(kd)}{kd} \right)^2 \right]$$

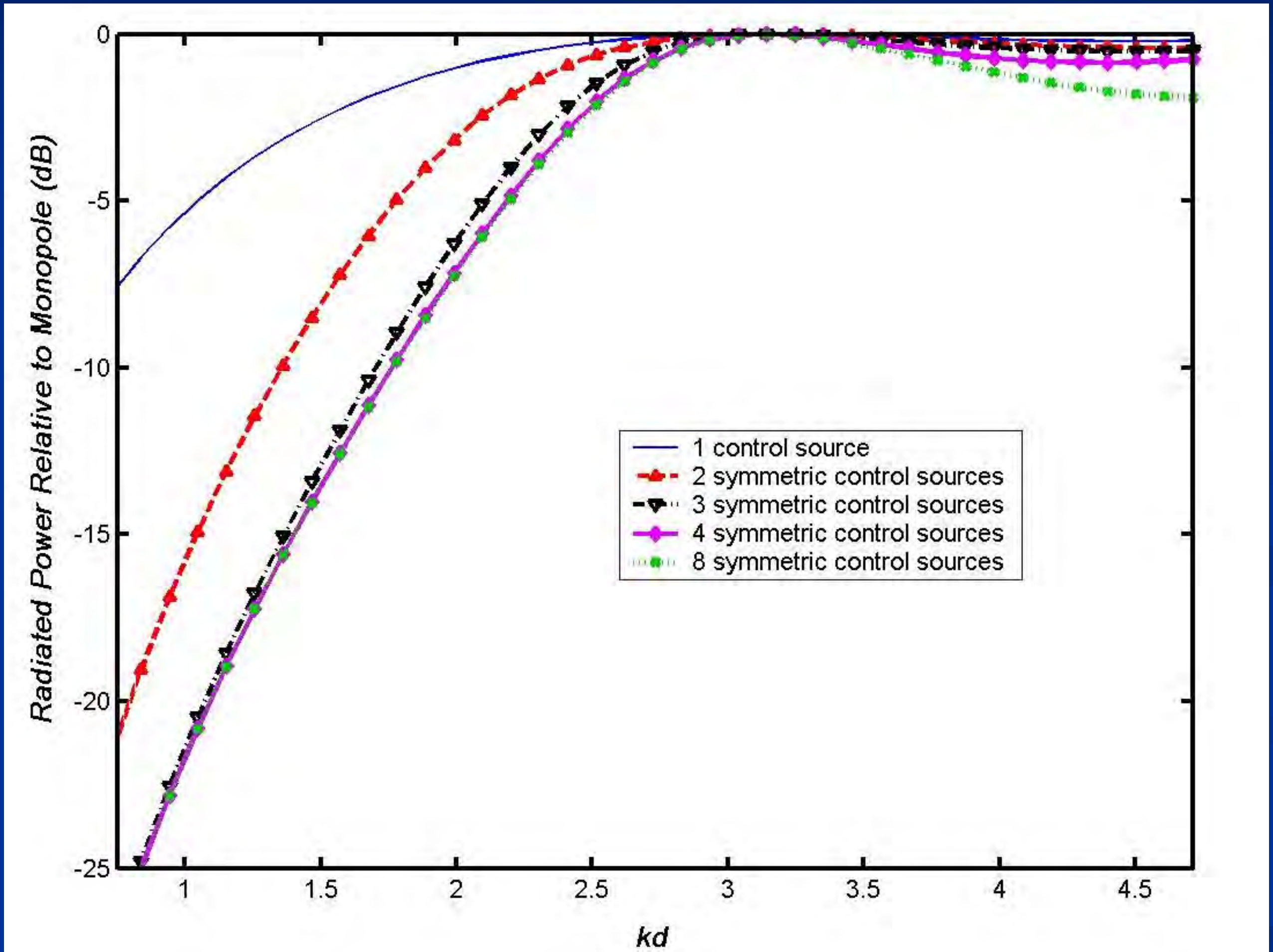
- For additional and/or more complex sources, same concept holds, but results expressed in terms of matrices

BYU Acoustics

# Free Field Radiation – cont.

- Control that can be achieved is a function of
  - Source spacing
  - Frequency
  - Number of control sources used
  - Geometric configuration of sources
- Power attenuation can be determined for various configurations
- Optimization is a more difficult problem, but needs to be looked at for maximum attenuation

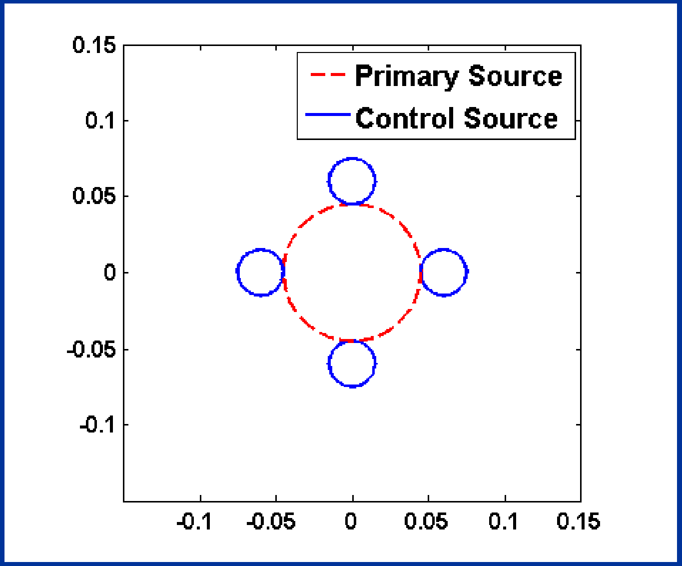
# Free Field Radiation – cont.

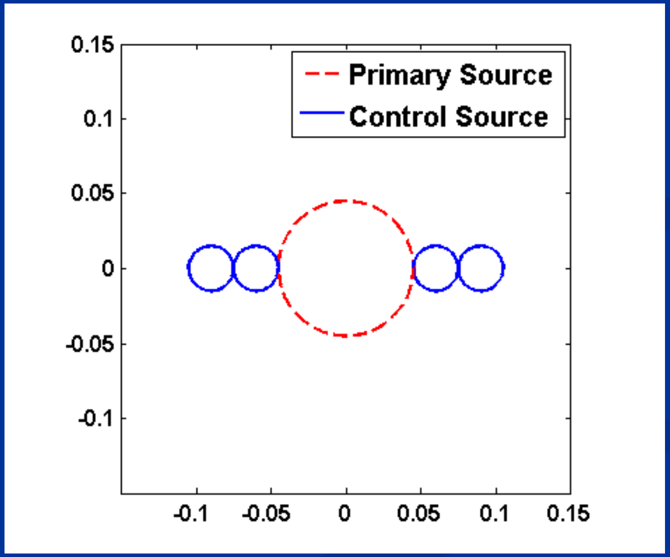



Power attenuation achieved for control sources in the plane of primary source

# Optimal Control Source Configuration

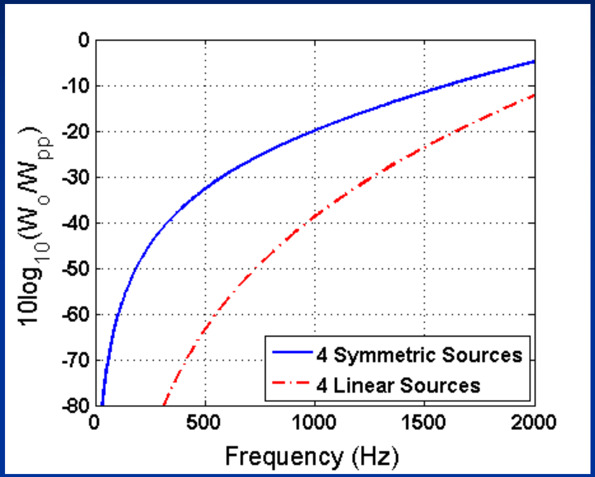
- Genetic algorithm used – look at potential source configurations, subject to constraints

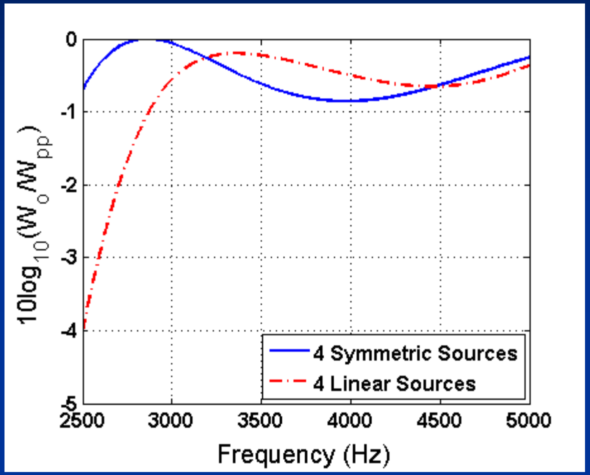


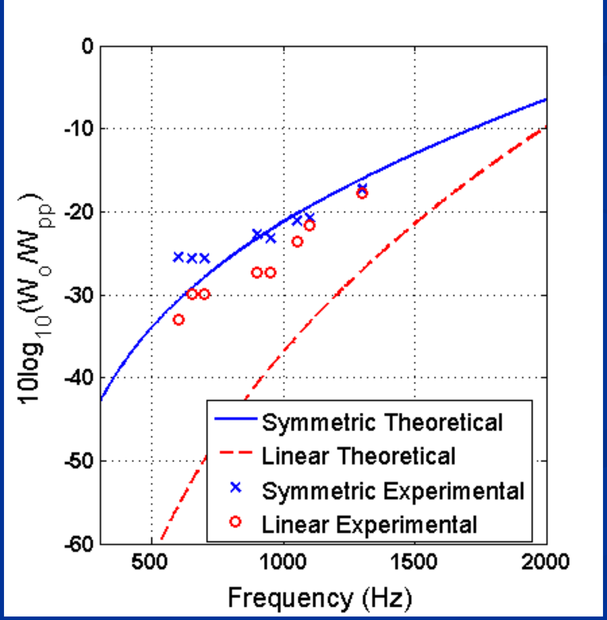




BYU Acoustics

# Comparisons of Symmetric/Linear Arrays




BYU Acoustics

# Global Control – Enclosed Sound Fields

- Global control still occurs through mechanism of source coupling, but in this case, sources couple through modes of enclosure
- Suggested that optimal solution for global control is to minimize overall potential energy (Nelson and Elliott)
- Requires integration of global energy, which is not practical – but starting point to determine system configuration



BYU Acoustics

# Enclosed Sound Fields – cont.

- Formally, can represent solution in terms of modes (single primary source, single secondary source)

$$\hat{p}(\mathbf{x}) = \sum_{N=1}^{\infty} \left(\hat{A}_N + \hat{B}_N \hat{Q}_c\right) \Psi_N(\mathbf{x})$$

$$\hat{Q}_c = -\frac{\sum_{N=1}^{\infty} \hat{A}_N \hat{B}_N^* \Lambda_N}{\sum_{N=1}^{\infty} \hat{B}_N \hat{B}_N^* \Lambda_N}$$

- Depends on all modal amplitudes, but does not have any spatial dependence
- For additional sources, matrix formulation applies

BYU Acoustics

# Enclosed Sound Fields – cont.

- Control solution depends on $\hat{A}_N, \hat{B}_N$

$$\hat{A}_N = j\rho c k Q_p(\omega)\frac{\Psi_N(\mathbf{x}_p)}{V\Lambda_N(k_N^2 - k^2)} \qquad \hat{B}_N = j\rho c k\frac{\Psi_N(\mathbf{x}_c)}{V\Lambda_N(k_N^2 - k^2)}$$

- Dependence on
  - Frequency
  - Source location(s), relative to primary source location(s)
  - Number of sources

# Error Sensor Design

- Previous results focused on source configuration – first step for achieving global control
- For implementation, requires measurement of sound power (free field radiation) or global potential energy (enclosed fields)
- These quantities not available in practice. Need to develop sensing schemes that approximate desired quantity as best we can
- Appropriate sensing scheme depends on application
- Example: Area (and shaped) piezofilm sensors for ASAC (Berry, Nelson & Elliott, Sommerfeldt); radiation mode sensing (Nelson & Elliott, Hansen, others)

BYU Acoustics

# Sensor Implementation – Free Field Radiation

- Application of interest is radiation from small axial fans
- Sound power is not easily available, particularly in real time
- Far field microphones could be used – not practical if a compact solution is desired
- Sensor approach developed based on microphones in near field

# Sensor Implementation – Free Field Radiation

- Approach based on analysis of power minimization
- After source configuration determined, analytical/numerical model of system developed and power radiation calculated
- Power minimization carried out to determine optimal source strength(s). For single control source,

$$Q_2 = -Q_1 \frac{\sin(kd)}{kd}$$



BYU Acoustics

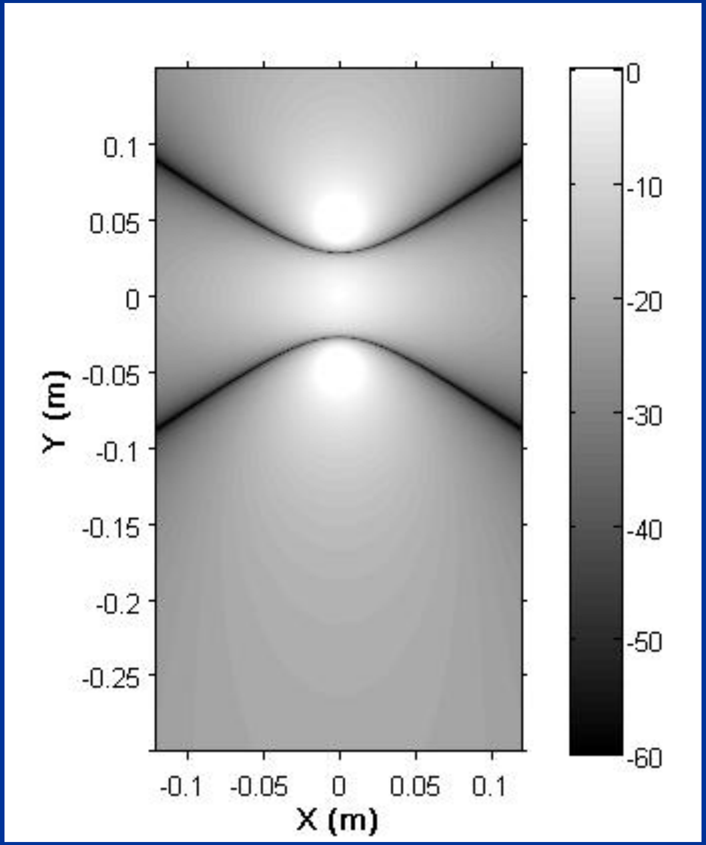
# Sensor Implementation – Free Field Radiation

- Using optimal source strength(s), near field pressure can be determined.
- Optimal error sensor locations are those where pressure attenuation is greatest when implementing optimal source strength(s).
- Near field nulls can be identified to indicate suitable sensor locations

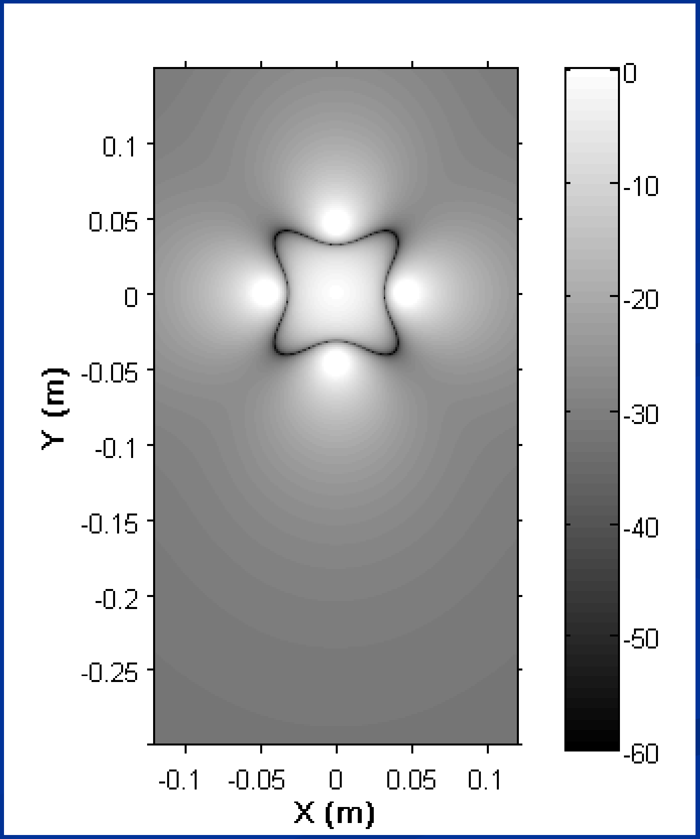
BYU Acoustics

# Sensor Implementation – Free Field Radiation

Pressure Field Reduction With Optimal Control Implementation (600 Hz, $d$ = 0.045m)



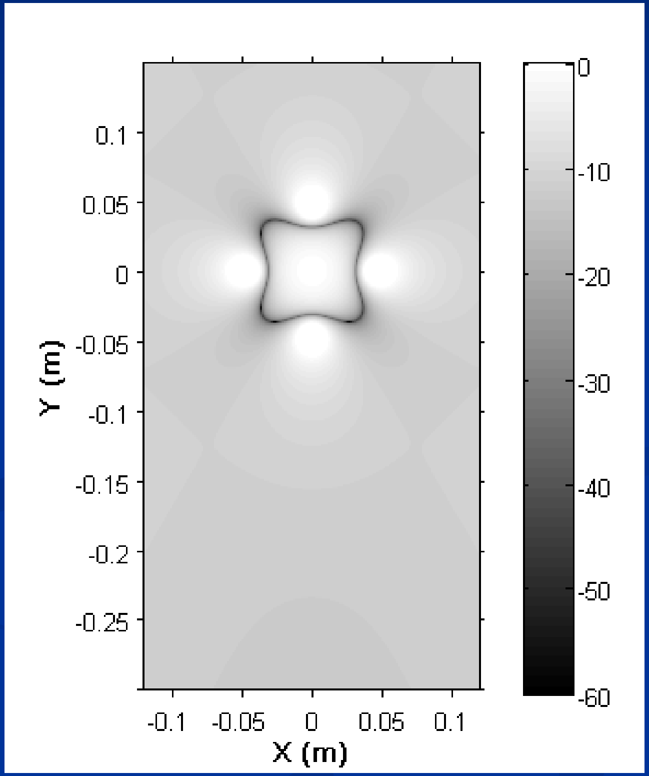

2 Control Sources




4 Control Sources

# Sensor Implementation – Free Field Radiation

- For co-planar sources, has been shown that nulls in plane of sources represent optimal locations (deepest nulls)
- Nulls have weak frequency dependence
- Method does rely on reasonable model of source radiation characteristics




1800 Hz

# Sensor Implementation – Enclosed Sound Field

- Ideally, need to measure global potential energy
  - Implementations with this strategy often result in high channel count for error sensors
- Alternative is to seek local measurement that provides information that is more global in nature
- One such possibility is the use of energy density
  - Sommerfeldt, Nashif, Parkins, Faber (Penn State/BYU)
  - Hansen, Cazzolato (University of Adelaide)

BYU Acoustics

$e = \frac{\hat{p}^2}{2\rho c^2} + \frac{\rho}{2}\hat{v}^2$ .

# Sensor Implementation – Enclosed Sound Field

- Energy density for *N*th mode given by

$$e_N(\mathbf{x}) = \frac{\hat{p}_N^2(\mathbf{x})}{2\rho c^2} + \frac{\rho}{2}\hat{v}^2(\mathbf{x})$$

$$= \frac{A_N^2}{2\rho c^2}\frac{1}{k^2}\left(k_x^2\cos^2(k_y y)\cos^2(k_z z) + k_y^2\cos^2(k_x x)\cos^2(k_z z) + k_z^2\cos^2(k_x x)\cos^2(k_z z)\right)$$

- Velocity estimated using pressure gradient

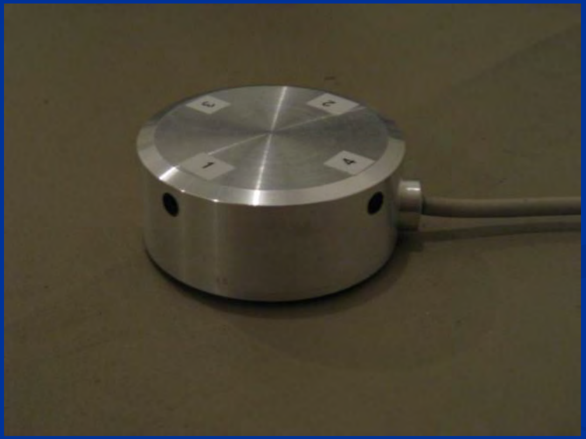
$$v_x = -\frac{1}{j\omega\rho}\frac{\partial p}{\partial x}$$

$$\approx -\frac{1}{j\omega\rho}\frac{p_2 - p_1}{\Delta x}$$

# Sensor Implementation – Enclosed Sound Field

- Prototype ED sensors

University of Adelaide



BYU – 2D

BYU – 3D

# Sensor Implementation – Enclosed Sound Field

- What makes ED sensors potentially better?
- Less spatial dependence for ED
- For 1D field (or axial modes), ED is uniform for mode
- For active control, need to have sensors away from nodes in order to effectively attenuate that mode

BYU Acoustics

# Control Solutions for Possible Control Strategies

- Global Potential Energy

$$\hat{Q}_c = -\frac{\sum_{N=1}^{\infty} \hat{A}_N \hat{B}_N^* \Lambda_N}{\sum_{N=1}^{\infty} \hat{B}_N \hat{B}_N^* \Lambda_N}$$

- Squared Pressure

$$\hat{Q}_c = -\frac{\sum_{N=1}^{\infty} \hat{A}_N \Psi_N(\mathbf{r}_e)}{\sum_{N=1}^{\infty} \hat{B}_N \Psi_N(\mathbf{r}_e)}$$

- Energy Density

$$\hat{Q}_c = -\frac{\sum_{N=1}^{\infty}\sum_{L=1}^{\infty} \hat{A}_N \hat{B}_L^* F_{NL}}{\sum_{N=1}^{\infty}\sum_{L=1}^{\infty} \hat{B}_N \hat{B}_L^* F_{NL}}$$

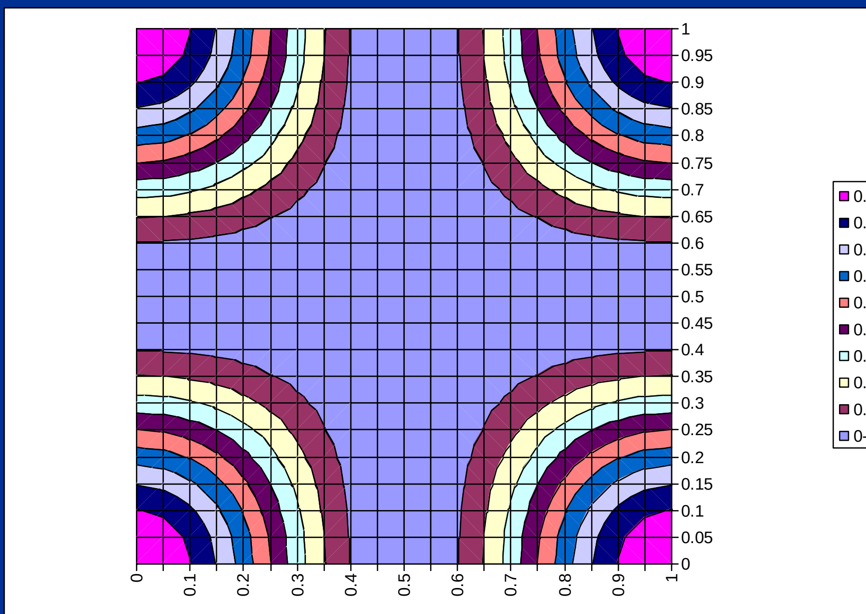
$$F_{NL} = \Psi_N(\mathbf{r}_e)\Psi_L(\mathbf{r}_e) + \frac{1}{k^2}\left(\frac{\partial \Psi_N(\mathbf{r}_e)}{\partial x}\frac{\partial \Psi_L(\mathbf{r}_e)}{\partial x} + \frac{\partial \Psi_N(\mathbf{r}_e)}{\partial y}\frac{\partial \Psi_L(\mathbf{r}_e)}{\partial y} + \frac{\partial \Psi_N(\mathbf{r}_e)}{\partial z}\frac{\partial \Psi_L(\mathbf{r}_e)}{\partial z}\right)$$



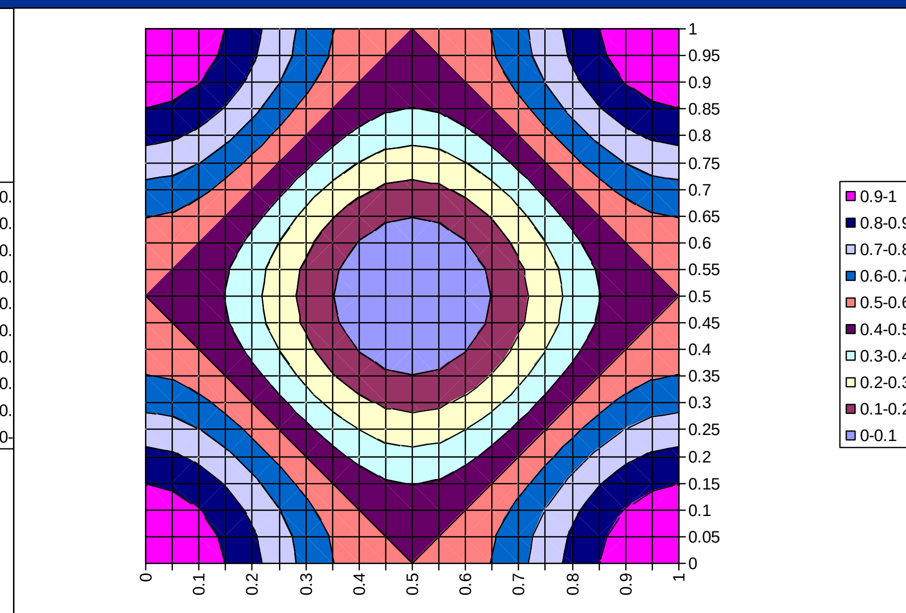
BYU Acoustics

# Spatial Dependence of Pressure vs. Energy Density

## (1,1,0) Mode

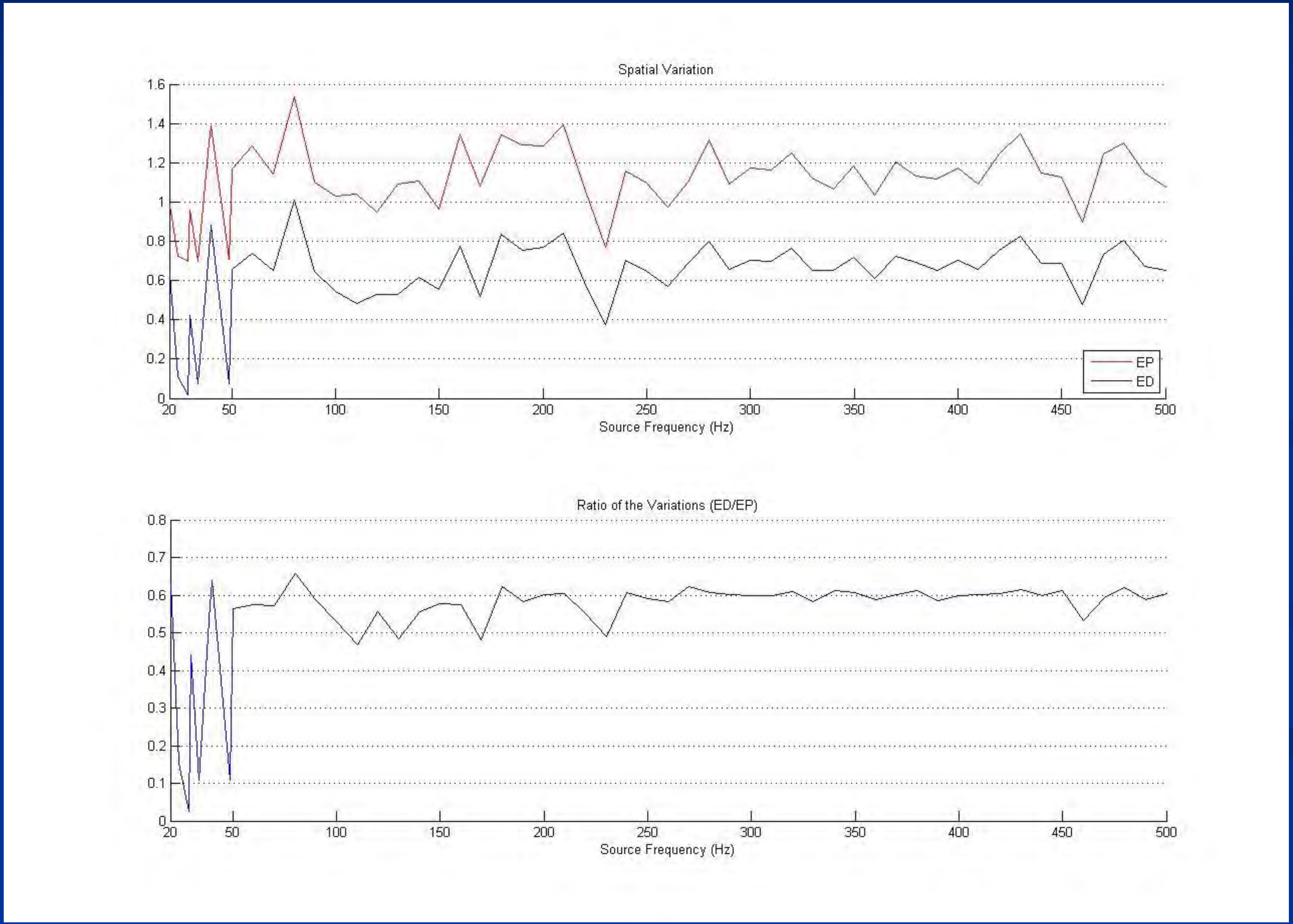


Pressure Response




Energy Density Response

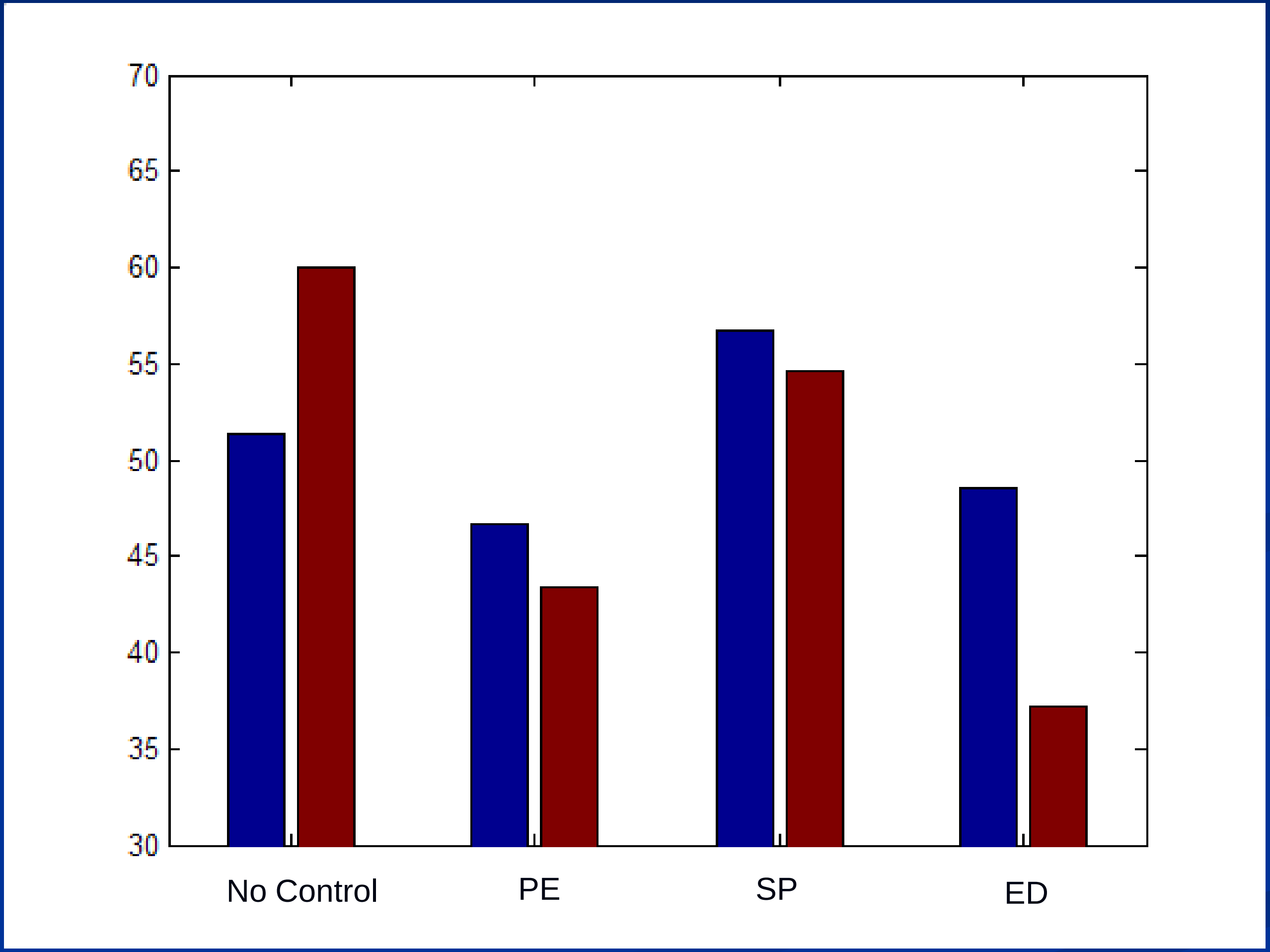
# Spatial Variation of Pressure vs. Energy Density – 3D Field



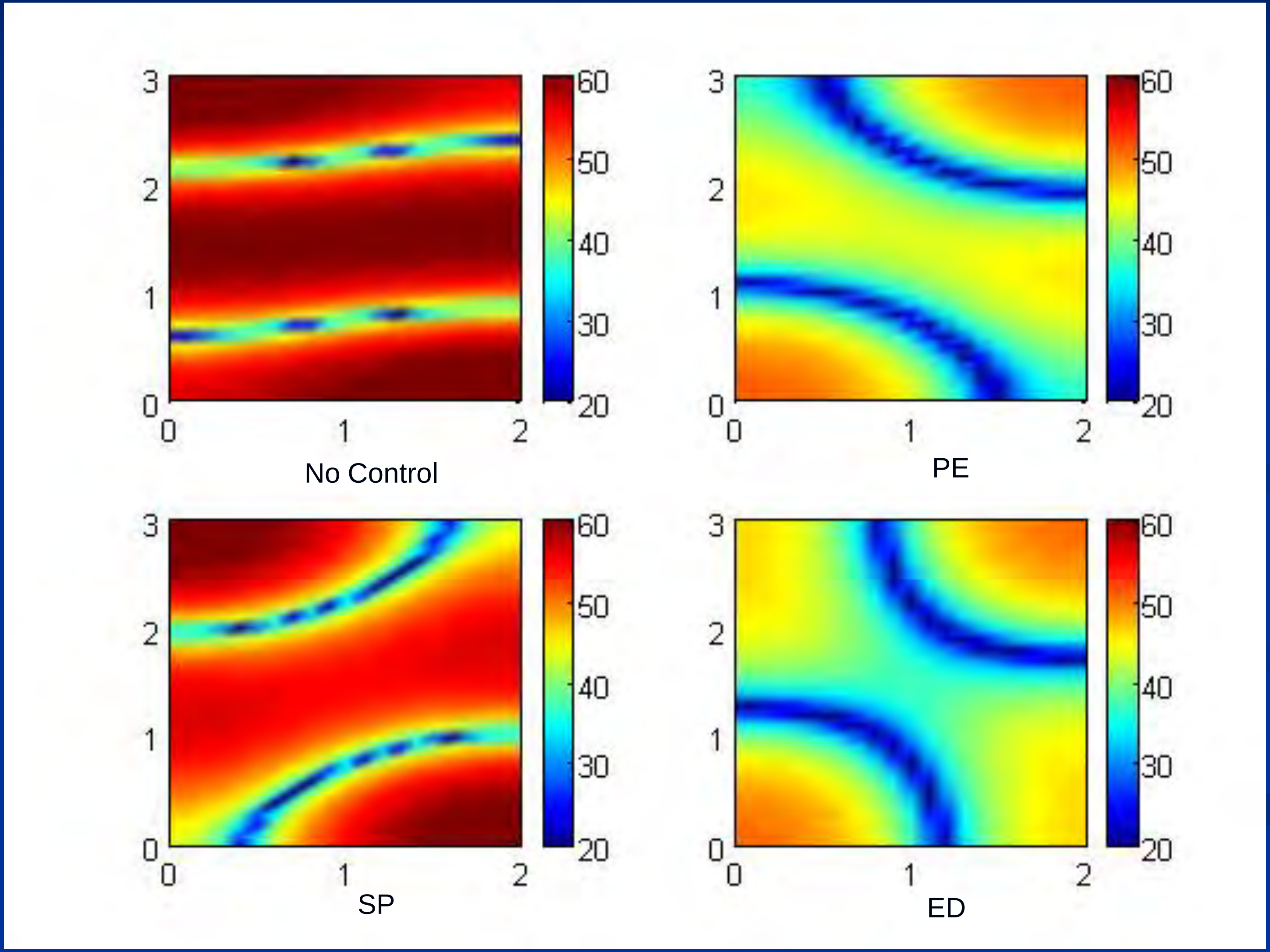



BYU Acoustics

# Example – 2 Mode Case

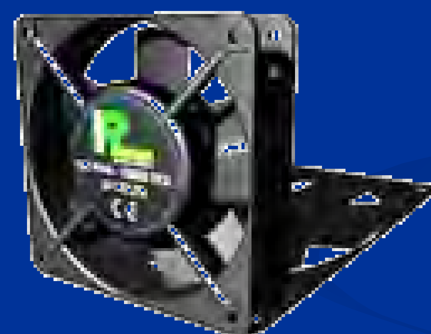


# Example – 2 Mode Case

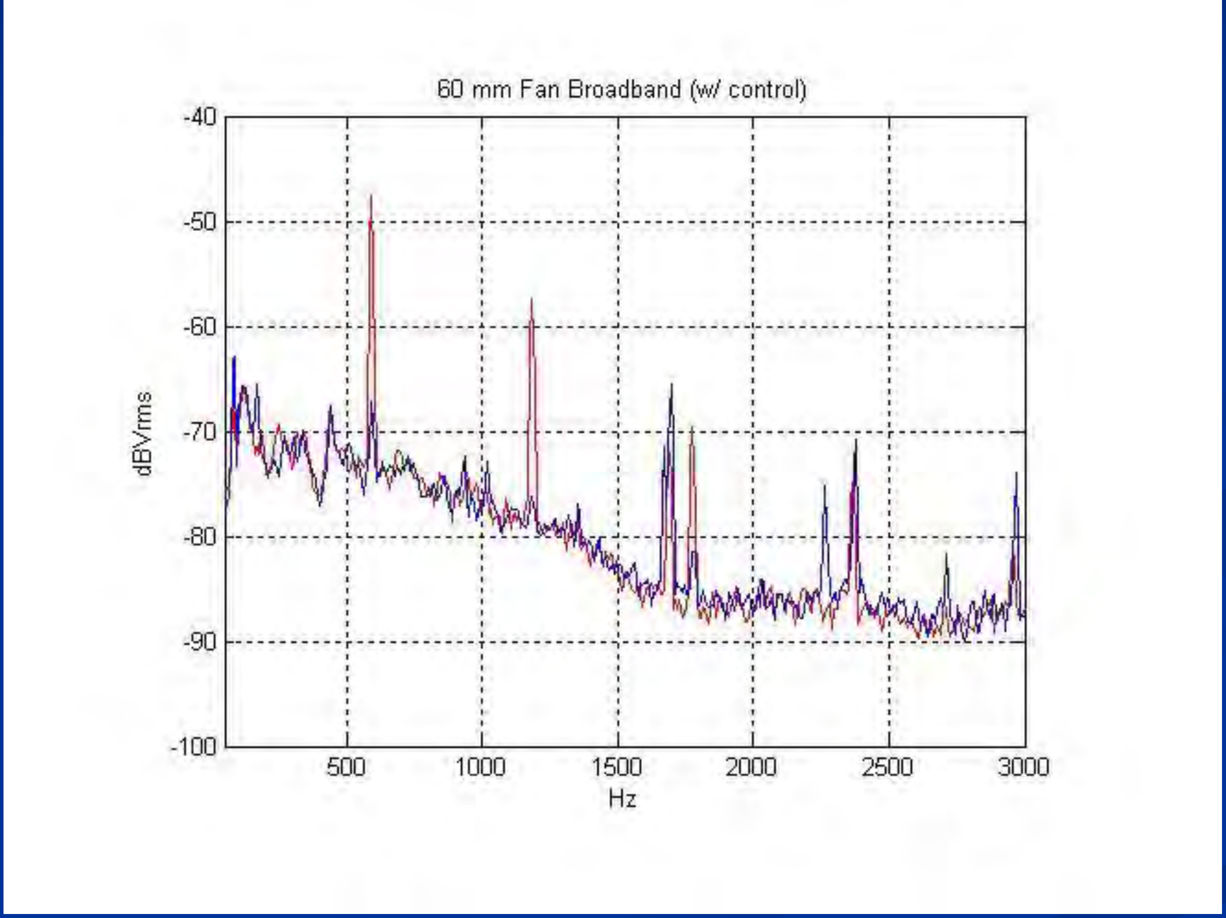


# Application – Axial Fan Noise

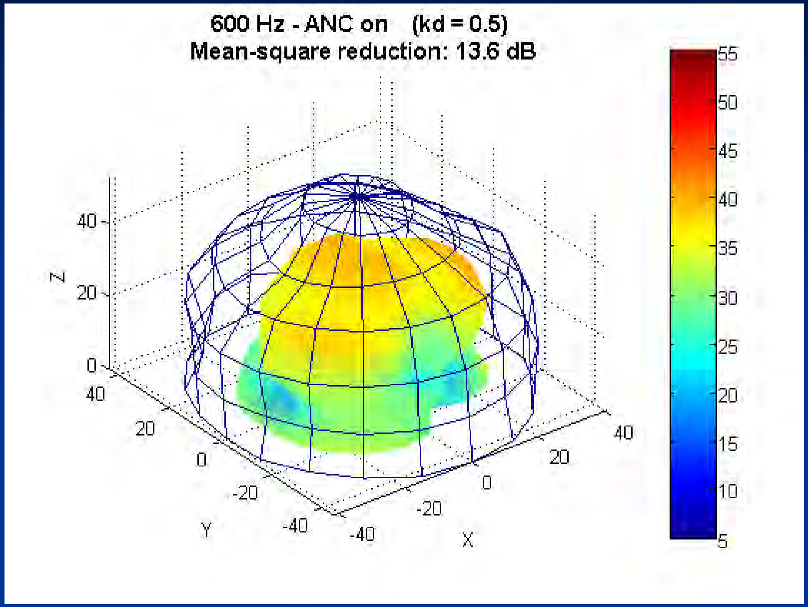
- Seeking global attenuation of radiated fan noise (tonal)
- 60 mm  and 80 mm fans

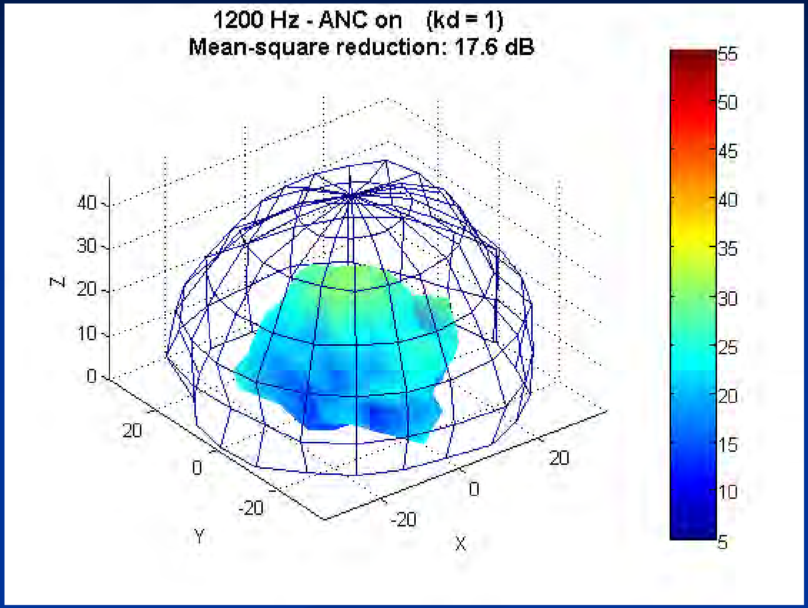


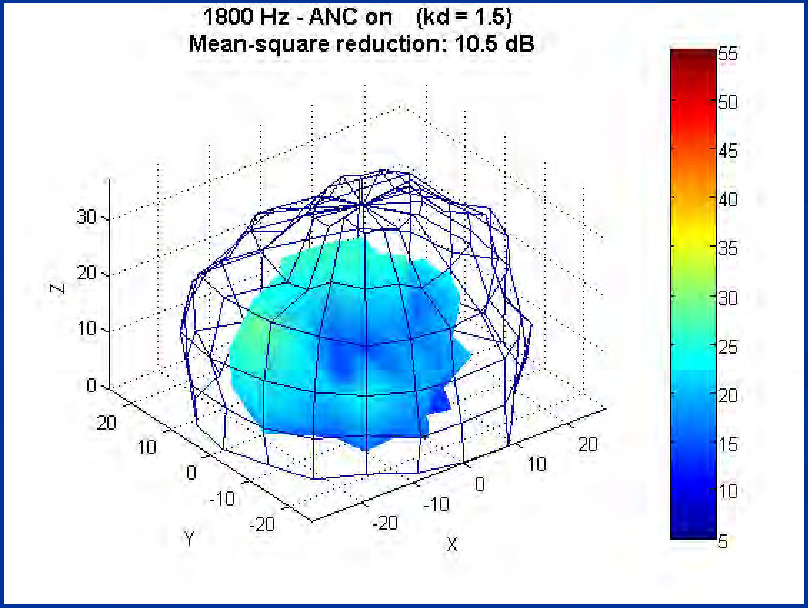
# Control Results – Far Field Mic



# 60 mm Fan Results – Global Response



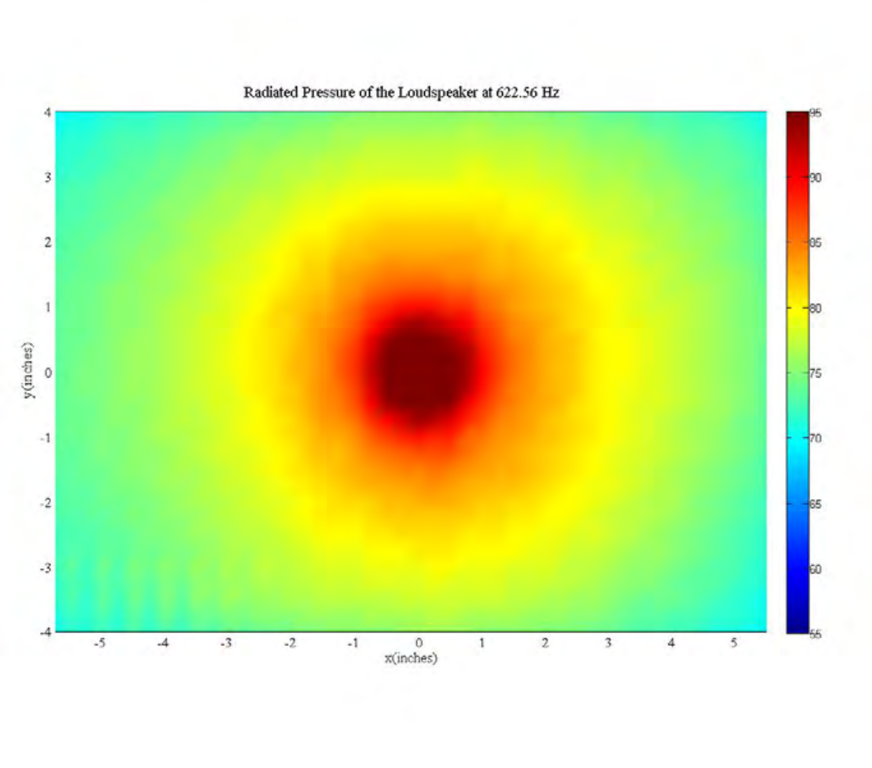



# Fan Results – Global Response

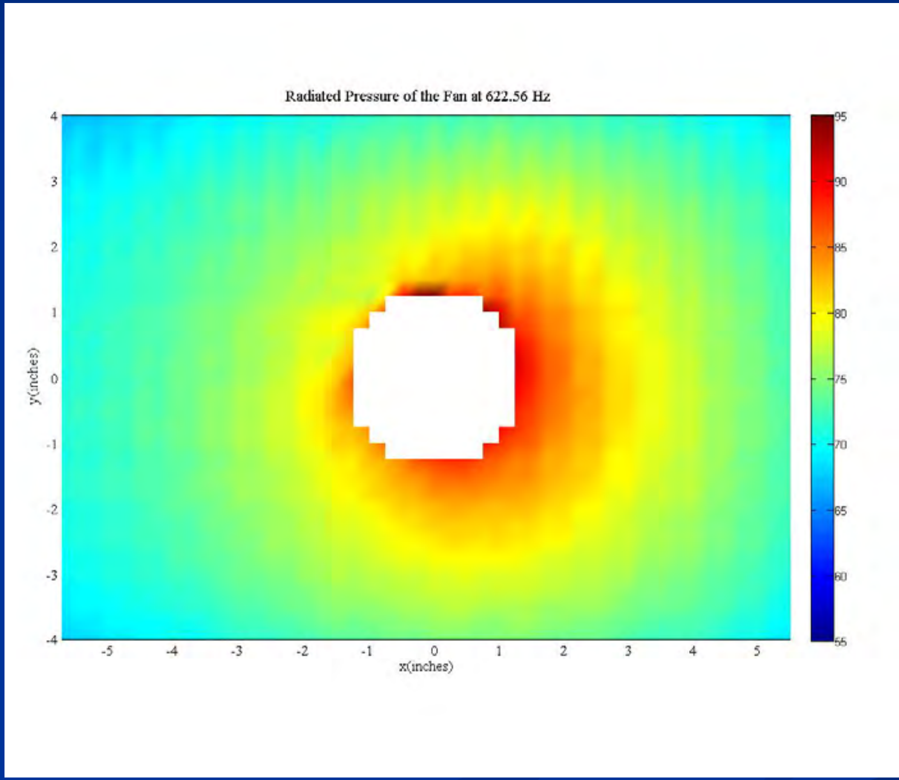
Global Mean-Square Pressure Reduction

| | 60 mm | | 80 mm | | Ideal | |
|---|---|---|---|---|---|---|
| | kd | MP R | kd | MPR | kd | MPR |
| BPF | 0.5 | 13.6 | 0.4 | 10.1 | 0.5 | ~30 |
| 2 X BPF | 1.0 | 17.6 | 0.8 | 16.1 | 1.0 | 22 |
| 3 X BPF | 1.5 | 10.5 | 1.2 | 12.8 | 1.5 | 14 |

# Near Field Response – No Control



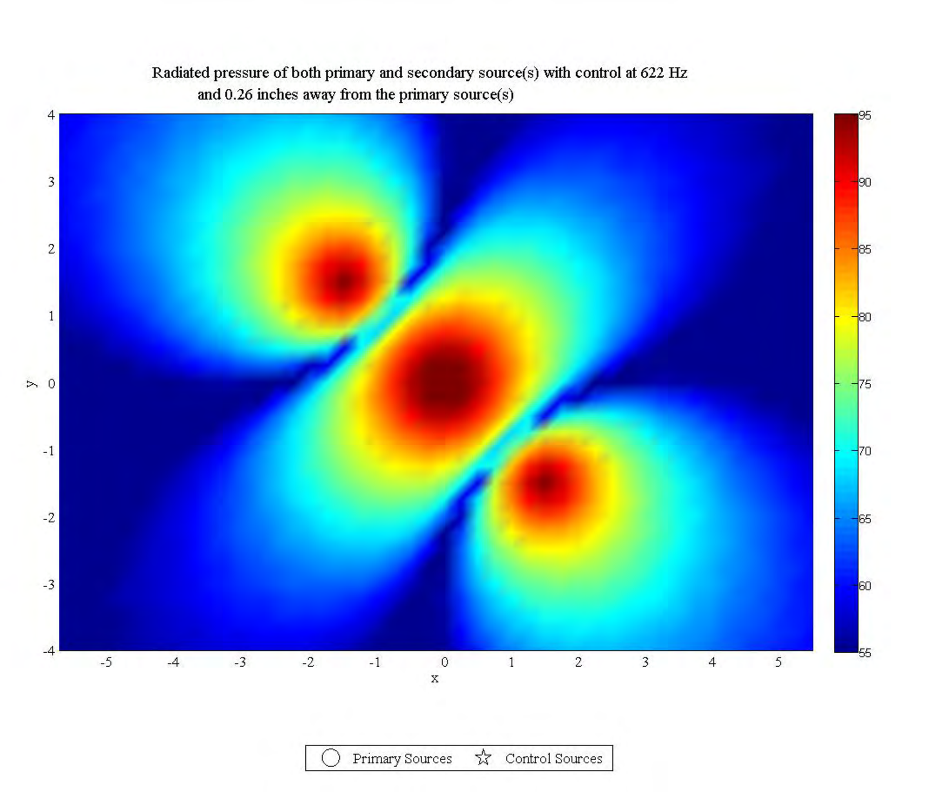

Speaker



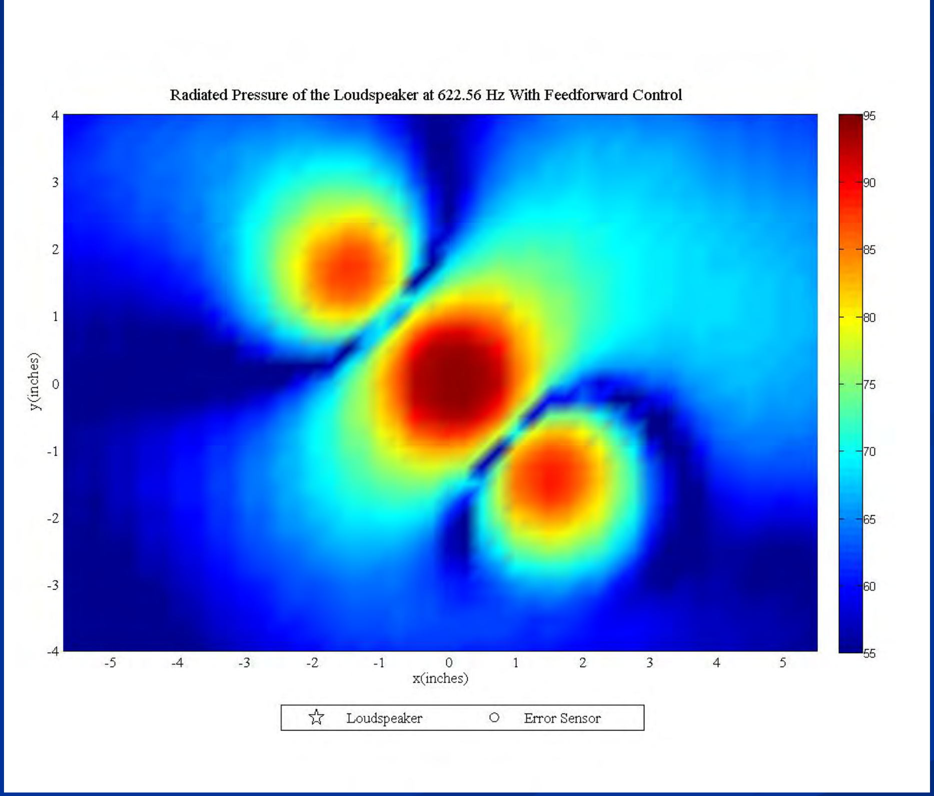

60 mm Fan

BYU Acoustics

# Near Field Control (Speaker) - 2 Channel Control



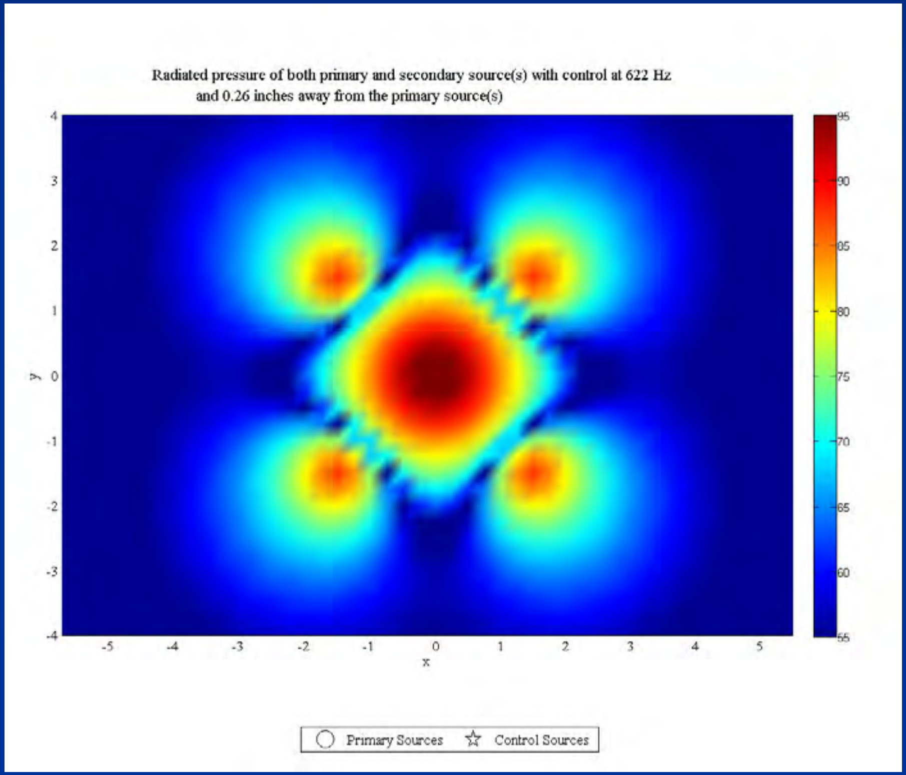

Theoretical Result



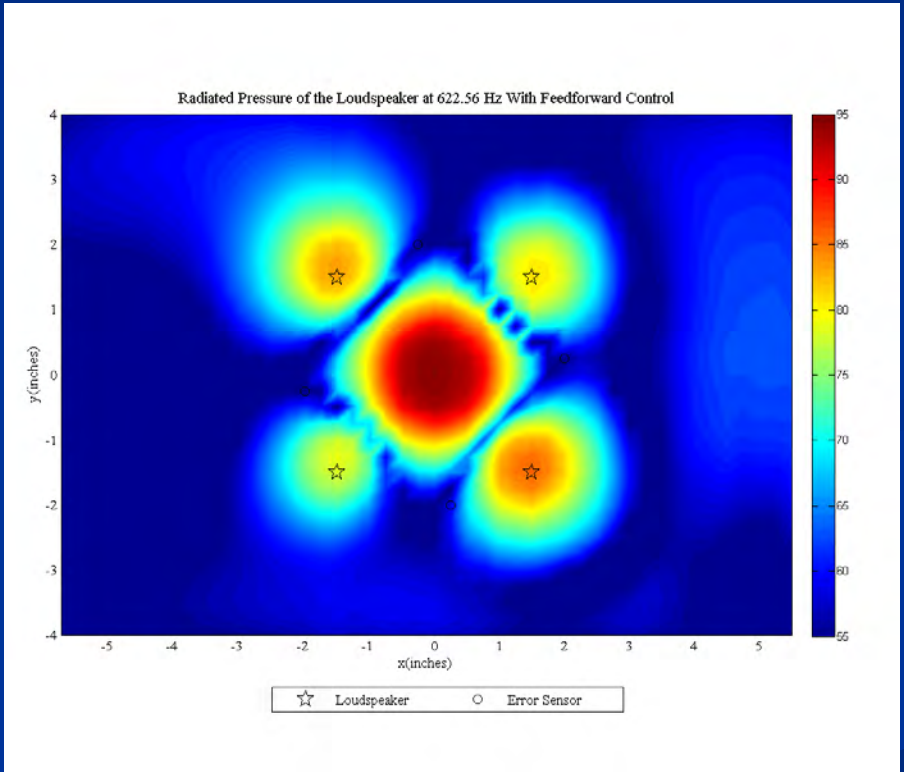

Measured Result

BYU Acoustics

# Near Field Control (Speaker) - 4 Channel Control

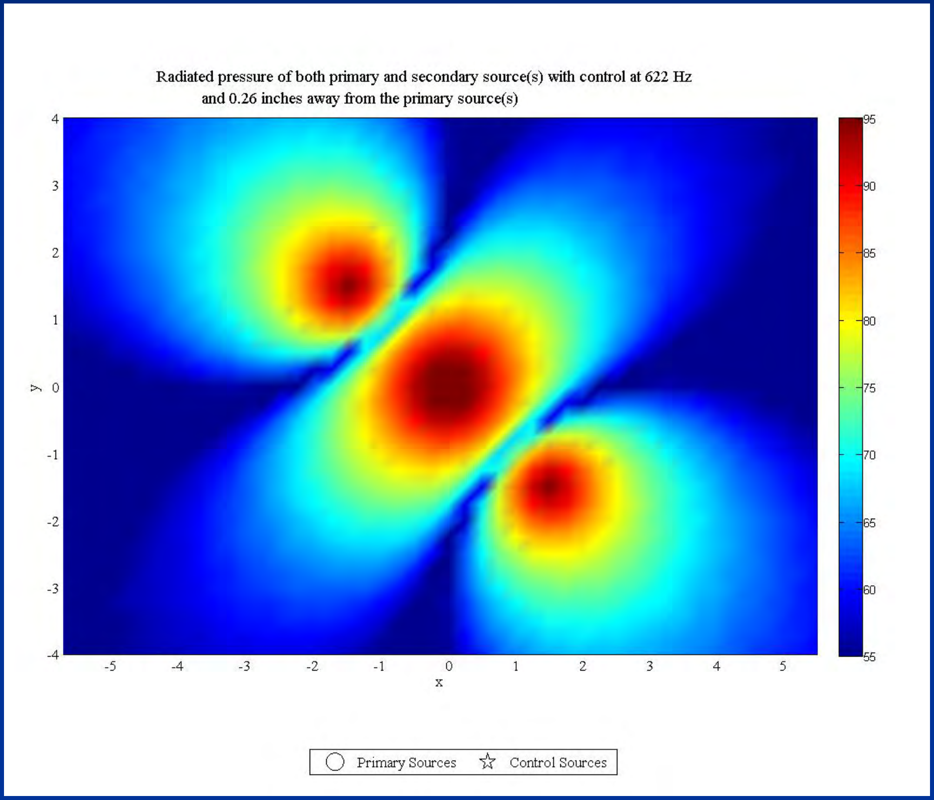



Theoretical Result

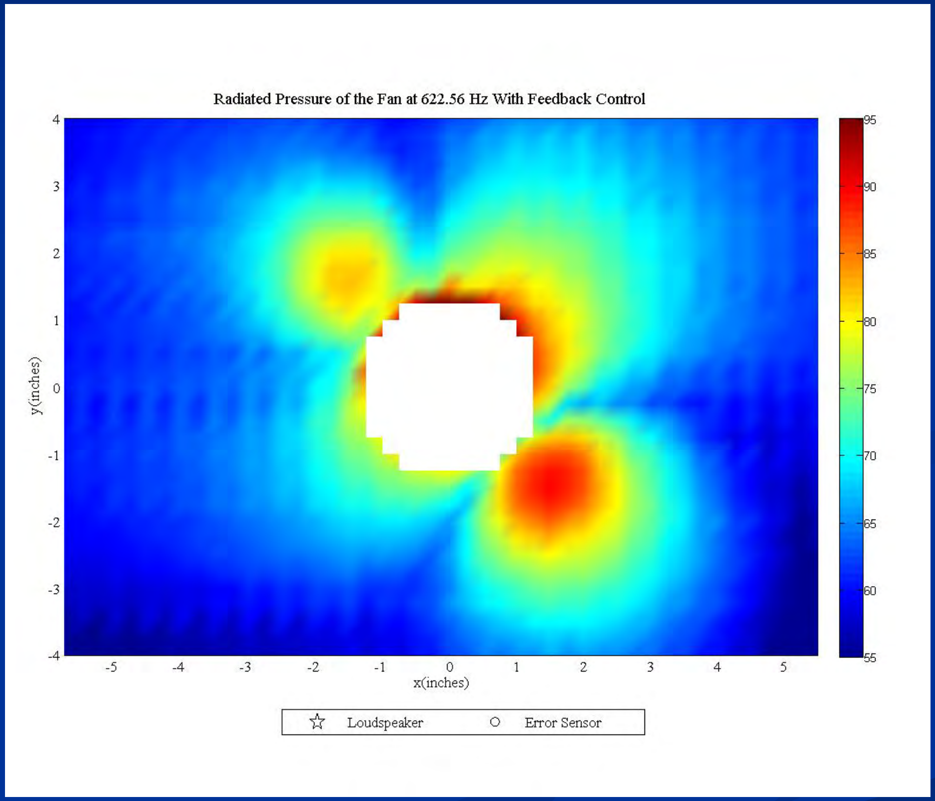



Measured Result

# Near Field Control (Fan) - 2 Channel Control

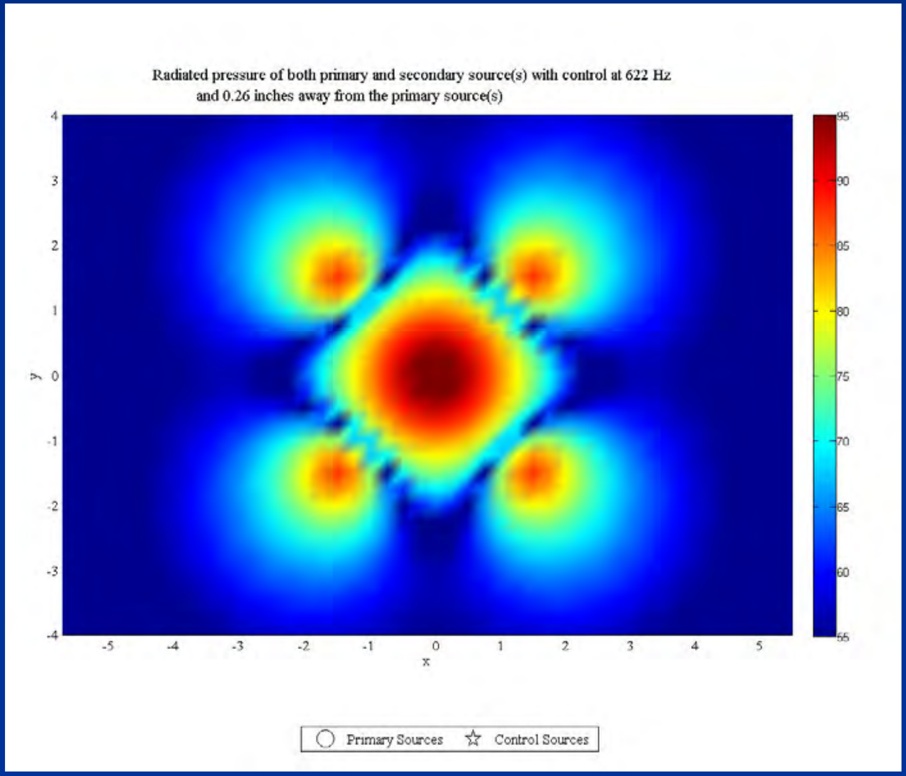



Theoretical Result

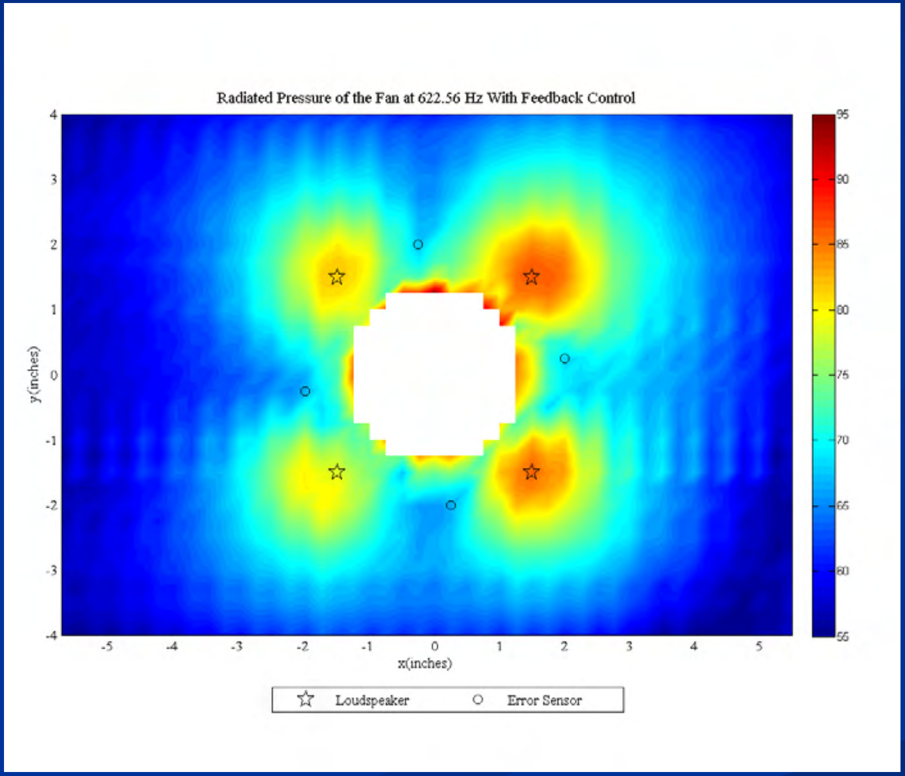



Measured Result

# Near Field Control (Fan) - 4 channel control

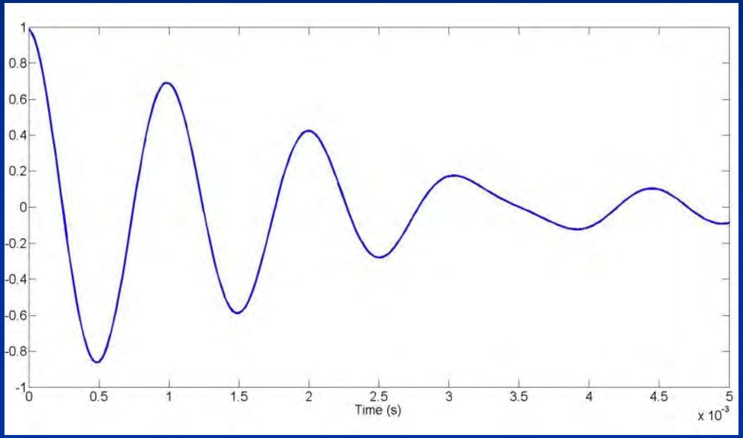



Theoretical Result

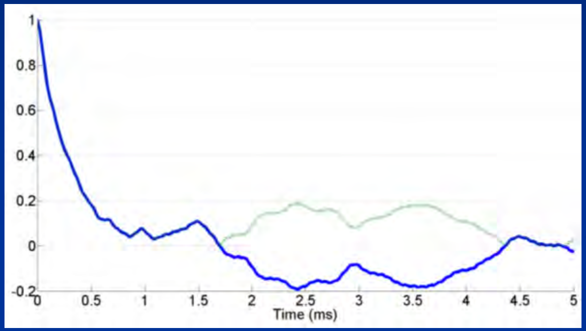



Measured Result

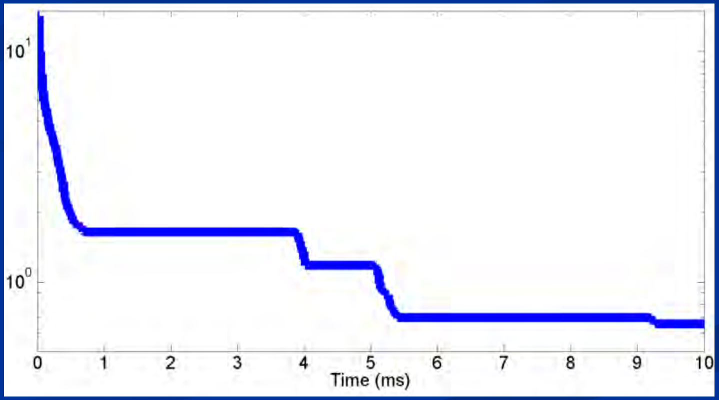
# Broadband Control – Theoretical Predictions




Loudspeaker Autocorrelation

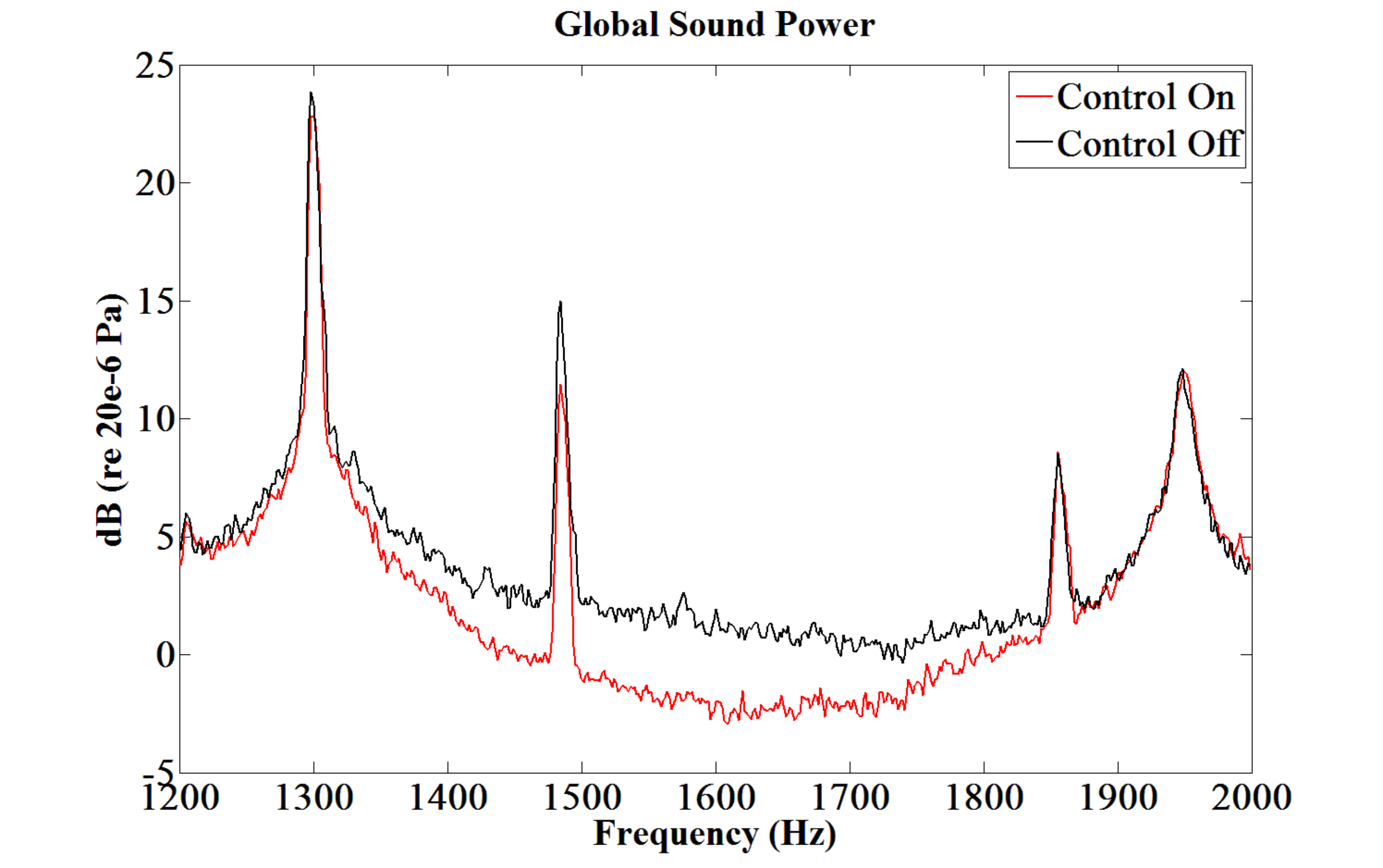



Fan Autocorrelation




$$Attenuation(dB) = -10 \times \log\left(1 - \frac{E_p}{E_{total}}\right)$$

# Broadband Control - Analog Feedback Control (1.2 dB reduction)




BYU Acoustics

# Application – Wheel Loader Cab Noise

- Interested in tonal noise associated with engine firing frequency

BYU Acoustics

# Filtered-x Algorithm for ED Minimization

- Cost function:

$$J = e = \frac{\hat{p}^2}{2\rho c^2} + \frac{\rho}{2}\hat{v}^2$$

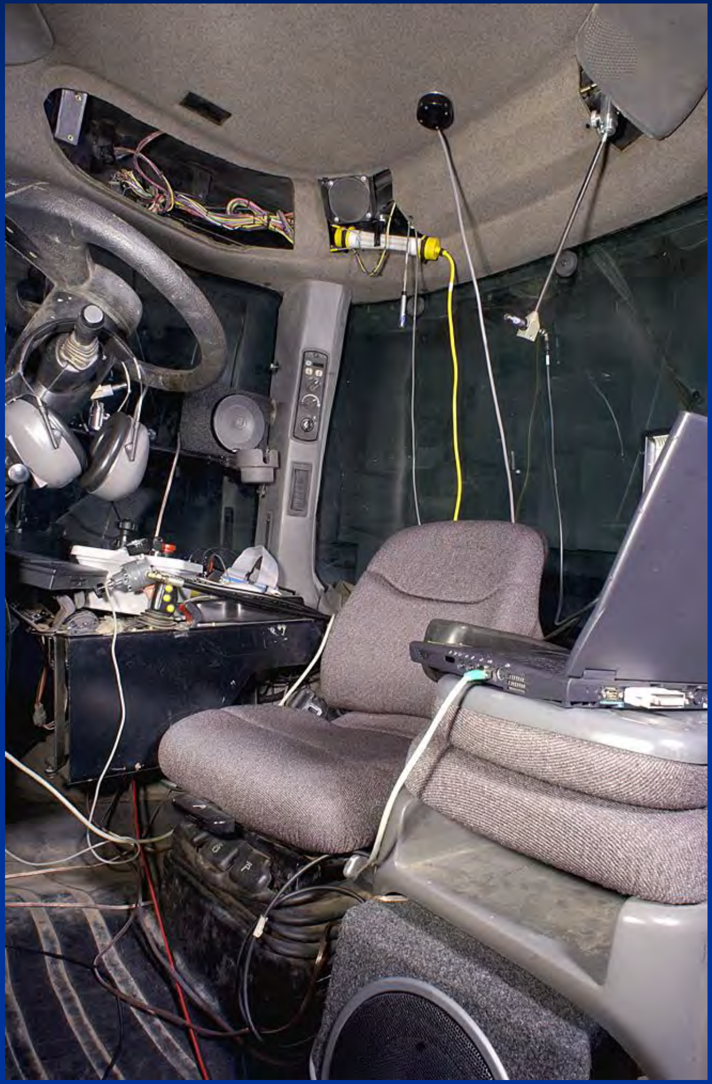
- Gradient of the cost function:

$$\frac{\partial J}{\partial W} = \sum_{m=1}^{3} \rho v_m(t)\mathbf{R}_{vm}(t) + \frac{1}{\rho c^2} p(t)\mathbf{R}_p(t)$$

- Update equation:

$$W(t+1) = W(t) - \mu\left(\sum_{m=1}^{3} \rho v_m \mathbf{R}_{vm}(t) + \frac{1}{\rho c^2} p(t)\mathbf{R}_p(t)\right)$$

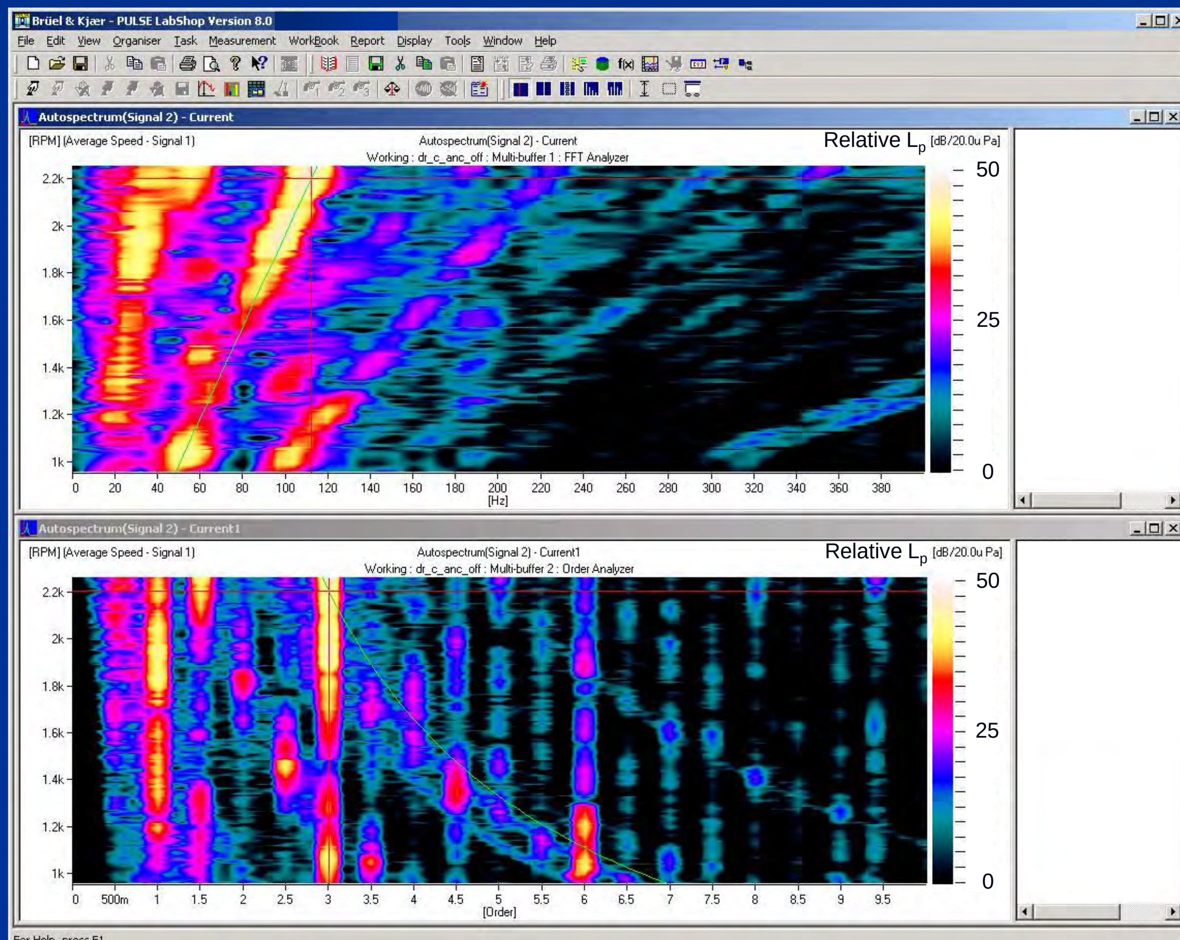
# Hardware Configuration



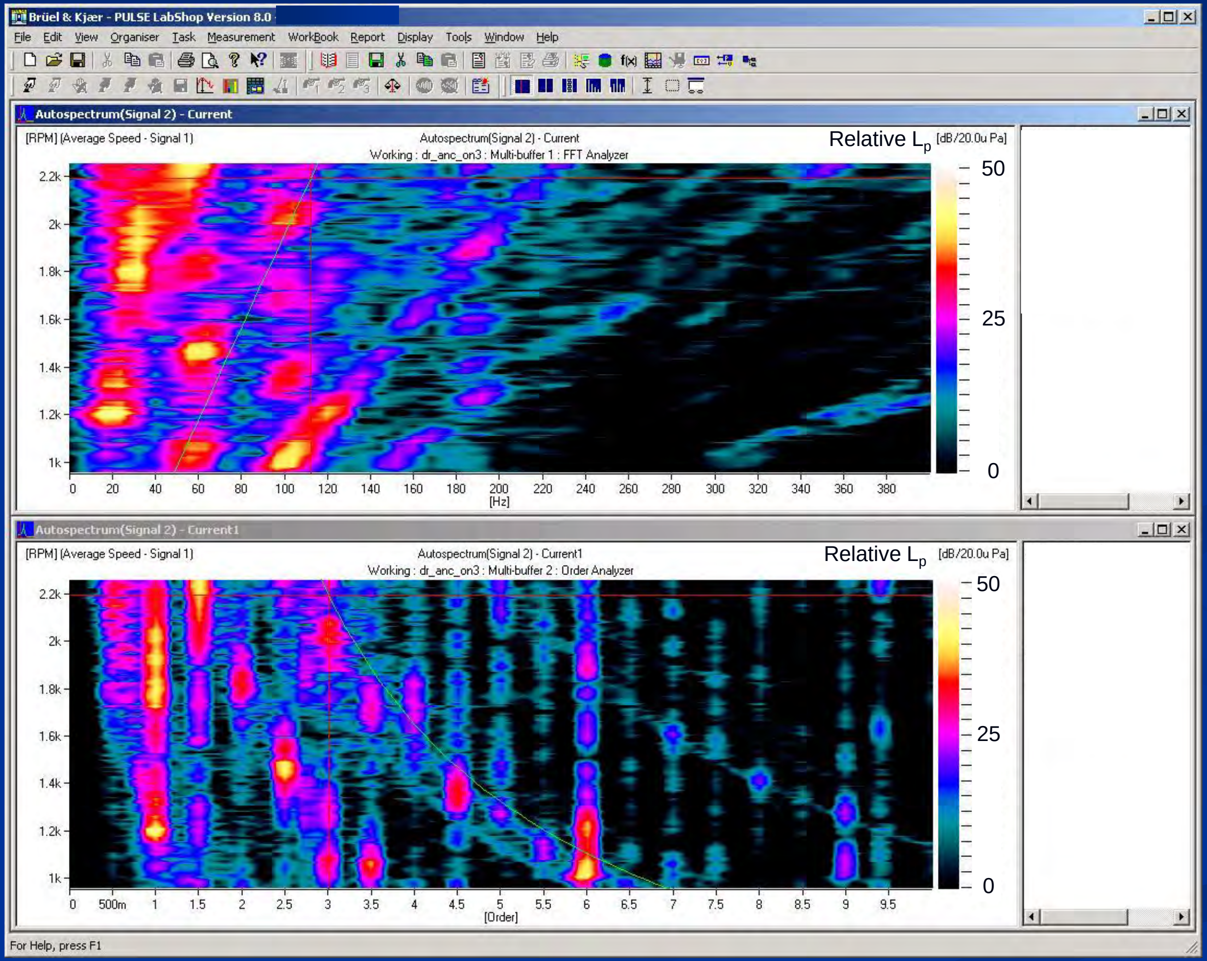
- Sub-woofer used for low frequencies
- Smaller drivers (10 cm) used for higher frequencies
- ED sensor mounted in convenient location

# Cab Response – Engine Sweep

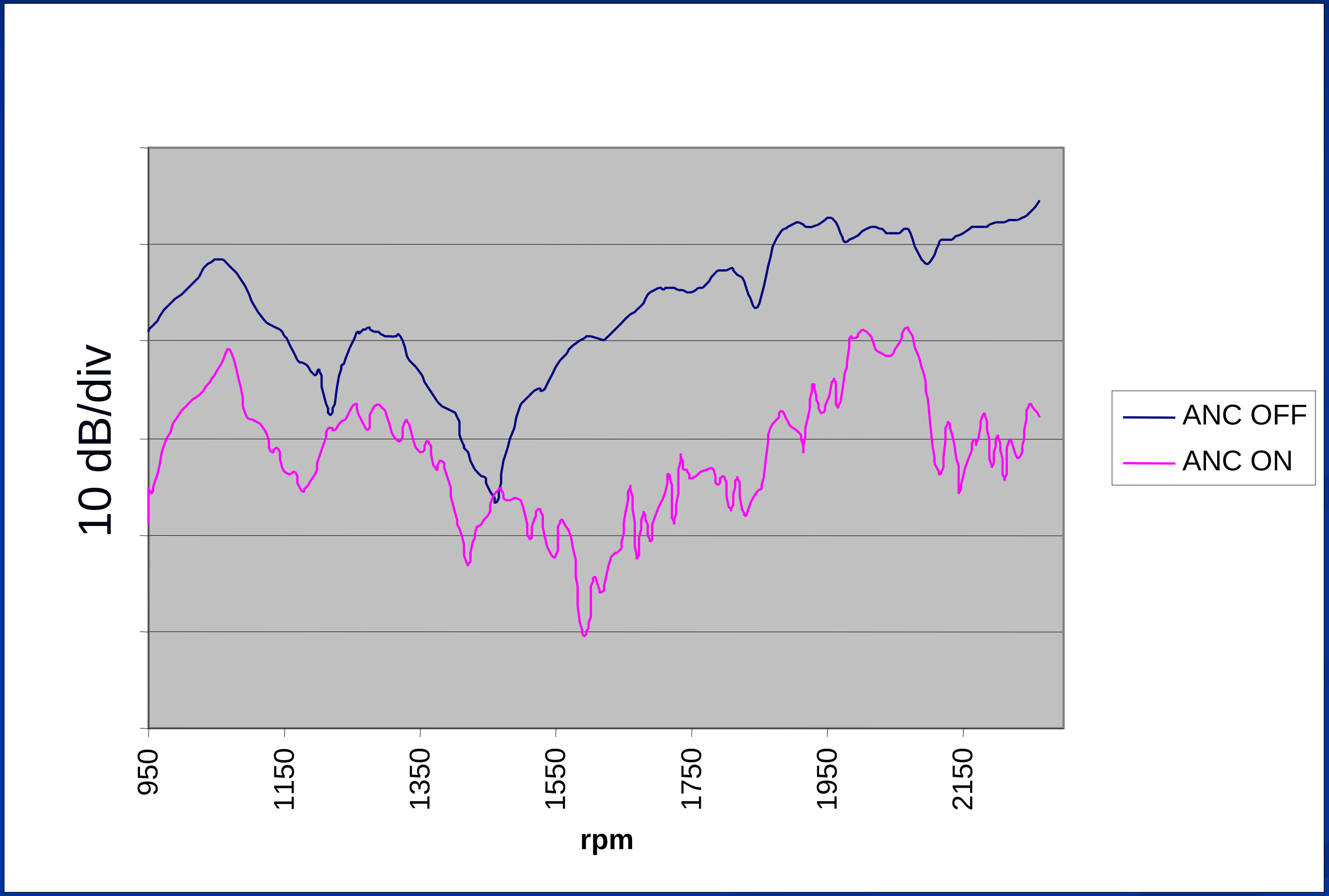
- Results measured at nominal operator head location



# Control Results – Engine Sweep



# Engine Firing Freq – Engine Sweep



# Cab Results – Global Response

- Overall A-weighted attenuation throughout cab

| | | |
|---|---|---|
| -3.4 | -2.2 | 0.1 |
| -6.3 | -6.4 | -5.0 |
| -8.1 | -7.5 | -5.2 |

operator head

upper plane

front

| | | |
|---|---|---|
| 0.2 | 0.9 | -1.1 |
| -2.5 | -3.9 | -1.3 |
| -5.7 | -5.0 | -5.2 |

lower plane

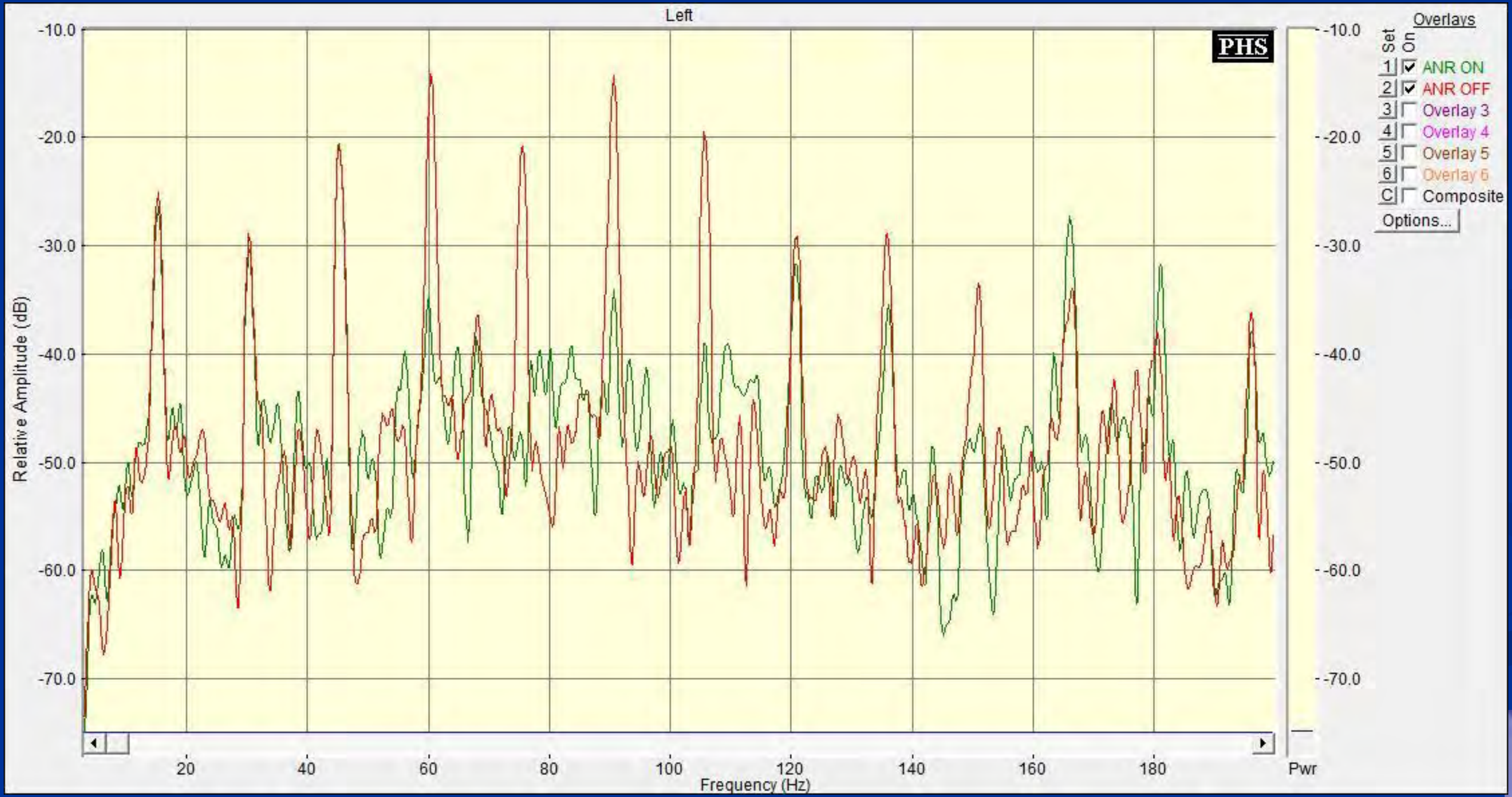
BYU Acoustics

# Locomotive Noise (NVH Technologies)

Class 66 Locomotive

# Locomotive Noise - Results

- Not only audible perception, but also perceived reduction in whole-body vibration




BYU Acoustics

# Summary

- Initial determination should establish what really needs to be accomplished
- Source configuration (number, type, location) should be established
- Sensor configuration (number, type, location) sould be established. Global sensing typically not feasible – what is best compromise?

BYU Acoustics

# Summary – Cont.

- For various applications, sensing techniques have been developed that can provide more global control
- Near field pressure sensors can be used for global control, if care taken as to their placement
- ED sensing is not the “ideal” solution, but does have strong tendency to provide larger region of control – more global in nature