# Active Minimization of Acoustic Energy Density to Attenuate Radiated Noise from Enclosures

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## Abstract

The noise produced by mechanical equipment can be an annoyance as well as a health and safety concern. One application where noise reduction has become important is in diesel power generators. Two methods for the reduction of noise exist: passive and active noise control. In this project active noise control (ANC) is applied to the problem of noise radiating from diesel generator enclosures.

The purpose of this research is to show that the active minimization of energy density within an enclosure can lead to a global reduction of the externally radiated noise. Two underlying questions will be answered in this research. Can the noise radiated from a diesel generator enclosure be effectively controlled by minimizing the energy density within? If so, does controlling the noise within the enclosure provide a global reduction?

Tests using a filtered-x LMS based adaptive ANC algorithm modified to minimize energy density (ED) have been conducted. These results show that A-weighted sound pressure levels (SPL) outside of a generator enclosure can be reduced by minimizing energy density within.

## Introduction

ANC is achieved by generating sound which destructively interferes with an unwanted noise field to provide cancellation.[1] It can be accomplished using feedback control, feedforward control, or a combination of the two.[2]

Feedback active control systems use a filtered and inverted output signal summed with the input signal to reduce noise. When these input and output signals add destructively, then feedback control is achieved.

Feedforward control uses a reference signal to anticipate the noise at some point in space.[3] This reference signal is used to generate a control signal that is produced 180º out of phase with the disturbance, thus canceling unwanted noise.[4]

## Background

Traditionally ANC systems use pressure microphones as error sensors and focus on minimizing the sum of the squared pressures or the potential energy associated with acoustic energy. Research within the last decade has shown that by minimizing acoustic energy density, a value consisting of both potential energy based on pressure and kinetic energy based on particle velocity, noise reduction is improved on a more global scale.[2]

The acoustic ED for an arbitrary location in a field is shown in Equation 1

$$w = \frac{p^2}{2\rho c^2} + \frac{1}{2}\rho \vec{v}^{\,2}, \qquad (1)$$

where $p$ is the acoustic pressure, $\rho$ is the ambient fluid density, $c$ the acoustic phase speed, and $\vec{v}$ the acoustic particle velocity.[5]

In order to minimize acoustic ED, a sensor capable of measuring acoustic pressure and particle velocity must be used. Acoustic pressure measurements can be made using a common pressure microphone. Particle velocity can be measured using two pressure microphones and finding a pressure gradient. From this value, an acoustic particle velocity can be calculated using a linear form of Euler's equation, shown below.

$$\rho \frac{\partial \vec{v}}{\partial t} = -\nabla p \qquad (2)$$

Since control was implemented in real time, a discrete value for particle velocity was used, where $\vec{v}$ was approximated using a digital integrator as shown in Equation 3.

$$\vec{v} = -\frac{\Delta t}{\rho \Delta x}\sum (p_2 - p_1) \qquad (3)$$

Here $\Delta t$ is $1/f_s$, where $f_s$ is the sampling frequency (2 kHz for this application), and $\Delta x$ is the distance between the two pressure microphones.[6]

## Methods

The experimental work for this research was performed on a 45 KVA, 4 cylinder, WhisperWatt™ diesel generator enclosure, shown in Figure 1.


**Figure 1** Apparatus to be controlled: 45KVA (36kW) diesel generator

This enclosure measures 200 cm x 90 cm x 125 cm (79 in x 35 in x 49 in). The goal of this research was to attenuate the overall A-weighted sound pressure level (SPL) radiating from the enclosure.

Results were obtained using a filtered-x feedforward control algorithm that minimized acoustic ED.

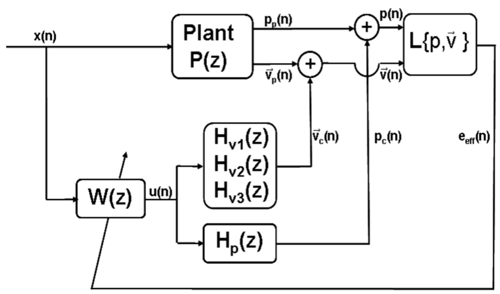


**Figure 2** Block diagram representation of a filtered-x feedforward control algorithm that minimizes acoustic energy density.[5]

The variable $x(n)$ is a measured reference signal. Acoustic pressure $p(n)$ and particle velocity $\vec{v}(n)$, measured at the error sensor, are comprised of pressure and velocity components from primary and control sources. $P(z)$ is the unknown plant, which is to be controlled. $W(z)$ is control filter, which adapts to minimize the ED at the error sensor. The $H(z)$ components are the measured transfer functions that model the path from the digital controller to the control source and then through the noise environment to the error sensor. L{v,p} represents signal processing, such as filtering, that occurs as the error signals update the control filter.[5]

For the results presented, one 8" SUB was used as the control source (see Figure 3). The reference sensor was a Larson Davis (LD) ½ inch ICP pressure microphone, connected to a LD PRM426 preamplifier. The error signal was measured using an acoustic ED sensor. The control was performed using a TMS320VC33 DSP processor and a custom I/O board. A Brüel & Kjær PULSE™ Sound & Vibration Analyzer


**Figure 3** Control source (8" SUB) mounted inside generator enclosure

was used for control measurements, and post processing was performed using MATLAB.

Control source location as well as error and reference sensor placement had to be optimized for desirable results. For all measurements, data was collected at the error sensor, located within the enclosure. Measurements were also made externally – near air intake and exhaust vents – these areas being the primary paths for noise radiating from the enclosure.

## Results

The results shown in Figures 4 and 5 were obtained using the control source configuration shown in Figure 3, where the error and reference sensors were mounted on the ceiling nearer to the engine.

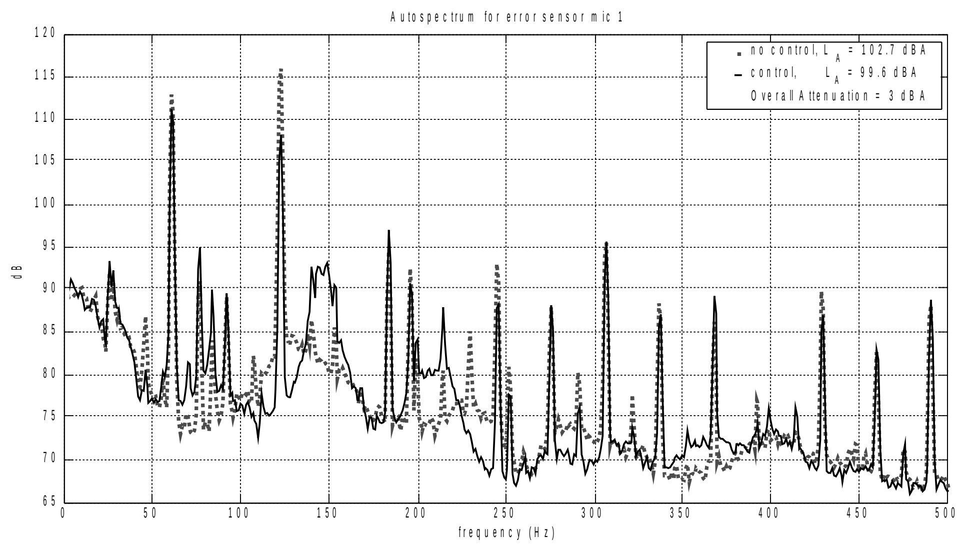


**Figure 4** Power-spectrum measurements showing acoustic levels for control and no control at the internally mounted error sensor

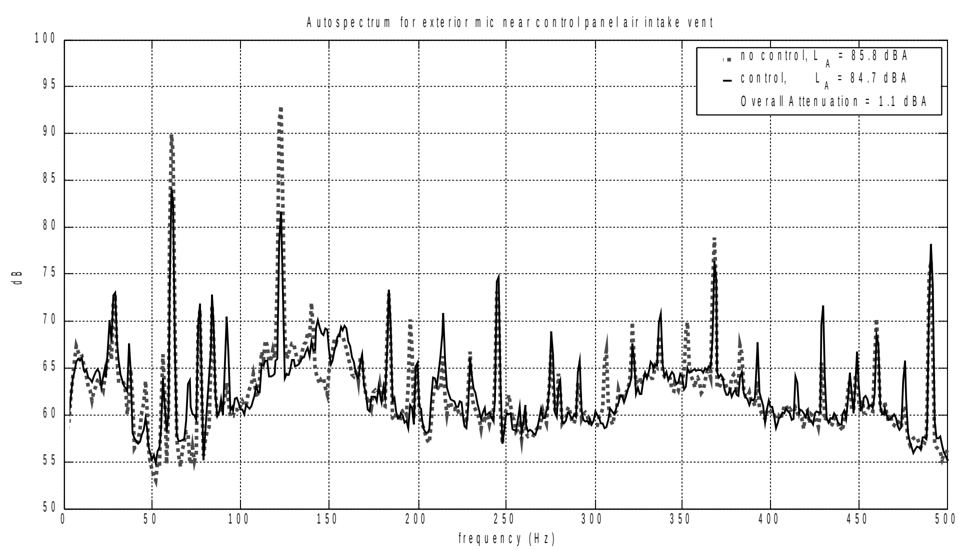


**Figure 5** Power-spectrum measurements showing acoustic levels for control and no control near an exterior air intake vent

Figure 4 shows the power-spectrum levels with and without control at the error sensor. The frequency band from 100 to 130 Hz is the best region of control and provides a broadband attenuation of 5 to 9 dB. Although other regions exist where control makes levels louder, the total effect of control leads to an overall sound pressure level (SPL) reduction of 3 dBA at the error sensor.

Figure 5 shows the power-spectrum levels with and without control at an exterior observational microphone. The most dominant frequency occurs at 62 Hz, which is the diesel engine firing frequency. When control is running this frequency sees an attenuation of 12 dB, while the first harmonic at 124 Hz sees an attenuation of 7 dB. This control provides an overall SPL reduction of 1.1 dBA.

Other observational microphones placed in exterior regions near air intake and exhaust vents saw similar results to those in Figure 5. Reduction was seen primarily at the engine firing frequency and the first harmonic. The overall SPLs were reduced at each location, although the reductions were not as great as those presented.

## Conclusions

These results show that minimizing ED at specific locations within the diesel generator enclosure can lead to a global reduction of the radiated noise. More tests are being conducted using a filtered-x feedback minimization approach to attain even great overall SPL reductions. Assuming positive results will be obtained using feedback control, a hybrid system will be developed that combines feedforward and feedback systems. Such a system would help maximize the attenuation of noise radiating from the enclosure.

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